

**NUMERICAL SIMULATION OF STRONG
DISCONTINUITIES IN A CONDUCTING
PLASMA**

THESIS SUBMITTED

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C E R T I F I C A T E

This is to certify that the work embodied in the thesis entitled "NUMERICAL SIMULATION OF STRONG DISCONTINUITIES IN CONDUCTING PLASMA" being submitted by KISHOR KUMAR SRIVASTAVA, M.Sc. for the award of the degree of Doctor of Philosophy of the Bundelkhand University Jhansi, has been carried out under my supervision and guidance, that the work embodied has not been submitted elsewhere for the award of any other degree and is up to the mark both in it's academic contents and the quality of presentation.

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P R E F A C E

The present thesis is an outcome of researches carried out by me in the field of "NUMERICAL SIMULATION OF STRONG DISCONTINUITIES IN A CONDUCTING PLASMA" under the supervision of Dr V.K. Singh, Ph.D in the department of Mathematics & Statistics Bundelkhand University Jhansi (presently Asstt. Professor, in the department of Maths, Longowal Institute of Engg. and Technology Longowal, Sangrur), is being submitted for the award of Ph.D. degree in Mathematics. The thesis has been divided into eight chapters, each chapter has been subdivided into a number of articles.

The first chapter is introductory. It gives in brief, an idea about shock waves, spherical and cylindrical shock wave, equations of motion and jump condition behind the shocks in magnetogasdynamics, radiation phenomenon, similarity Principle, characteristic method, artificial viscosity and Withom's rule.

The second chapter is devoted to unify study of magnetoradiative shock wave propagation in conducting plasma, taking line explosion in a gas cloud and a detail study is made for the propagation of spherical and cylindrical shock wave. Numerical integration of differential equations of motion is done on D.E.C 1090 computer at I.I.T Kanpur by well known R.K.G.S Programme.

Chapter third deals with self similar magnetogasdynamic cylindrical shock waves with transverse and azimuthal axial magnetic field. The motion of gas is assumed to be adiabatic and

total energy of the wave remain constant . In this chapter instantaneous release of energy along a line in a gas cloud is assumed . A comparative study is made between cylindrical shock wave with transverse and axial magnetic field. Numerical integration of differential equations is carried out on DEC 1090 computer system at I.I.T Kanpur by R.K.G.S programme .

In fourth chapter , an attempt is made for the study of spherically symmetrical strong discontinuities with increasing energy in generalized Roche model and numerical solution are also obtained when the radiation heat flux is more important than the radiation pressure and radiation energy . The effect of magnetic field has also been taken into account .

Fifth chapter consists of analysis of self similar motion in the theory of stellar explosion, taking Newtonian gravitation into account. A thorough analysis of self similar equations of gas dynamics, under the effect of magnetic field is developed. A number of new solutions has been obtained in which radial oscillation of gas occur after the shock wave passes .It is supposed that star is in equilibrium state .

Sixth chapter deals with the study of an exact solutions of normal shock wave of variable strength advancing into a region of variable density taking pressure as constant and density varies according to a power law .

In seventh chapter, an attempt is made for the analytical solution of cylindrical shock wave in a rotating gas with azimuthal magnetic field ,taking density as constant ahead the

shock front. By using C.C.W method, analytical solutions are have been obtained for shock velocity and shock strength for weak and strong magnetic field. For strong shock, also we have considered two cases ie. when the magnetic field is strong and when weak, ie. non magnetic case.

Eaighth chapter consist, the effect of artificial viscosity on the explosion of discontinuities in a rotating interplanetary medium, an analytical solution where a very thin velocity gradient exists has been obtained. The concept of artificial viscosity suggested by Ritchmyer - Von Neumann has been introduced. It is assumed that velocity gradient is function of coordinates only. The effect of coriolis force has been considered due to circular rotation of medium in the space. Expressions for two different cases, the weak shock strength and the strong shock strength are obtained.

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CHAPTER - I

INTRODUCTION

(1) SHOCK WAVES :-

When disturbances of finite amplitude are propagated in perfect fluid or gases that is those with no viscosity or heat conductivity, discontinuities in pressure and velocity to the medium may occur. These are called shock waves or shock. The reason for their development may be seen in the case of one dimensional flow such as occurs in a tube of uniform cross section when a disturbance caused by the motion of a piston at one end is propagated down the tube. The principles of conservation of mass, momentum and energy is still apply across these plane discontinuities. These disturbances propagated through out the fluid as a wave motion and with the speed of sound relative to the fluid without suffering any destoration. It may be pointed out that shock wave is a surface of discontinuity, pulse like in nature and is sometimes more appropriately called shock front ([1],[2],[3],[4]). In general discontinuity surfaces are of two type - contact surface and shock front. A contact surface is a surface separating two parts of the medium with out any flow of a gas through the surface. A shock front is a discontinuity which is crossed by gas.

The velocity $[u]$ of the piston at any time is communicated to the gas and propagates down the gas with velocity of sound $[c]$ relative to the gas. Hence relative to the tube the velocity is propagated with the speed $(c + u)$ in the direction away

from the piston. Now if the piston moves to compress the gas in the tube that is, to decrease the volume of the gas, then the velocity of the gas increases since the temperature and density increases. Thus the greater the velocity, the greater the speed with which it is propagated if this process continued indefinitely, lesser velocities would be over taken by greater ones and we would have two values of the velocity at a given place in the gas which is impossible.

However, before this occurs there will be a time at which the velocity profile of the gas, that is the velocity distance curve, has a vertical shape. In this case, the differential equation governing the motion break down and the basis for the statement that the fluid velocity $(c + u)$, is no longer true.

Before formulating these laws for a perfect fluid it may be pertinent to point out that it is consequence of the non - linear character of the equations governing the propagation of finite disturbance ; that is in part responsible for the prediction of the formation of the discontinuities. Thus in the example mentioned above it is essential to the argument that the local velocity of sound (c) be greater at points where the velocity of the gas is larger than velocity of sound. This is the case for a compressive motion of the piston because the disturbance which have passed over the gas have changed its character (when heated it) and hence subsequent disturbance are travelling in a defferent medium than the original one. Taking in to account the change in the medium produced by one part of the phenomenon in the discussion above, subsequent part is accomplished mathematically by the non linear terms in the equation of motion.

The non - linear character alone is not enough to cause discontinuities for it, in the example given above, the piston motion were such as to increase the volume of the gas in the tube, that is, if a rarefaction wave propagated down the tube then the local velocity of sound would decrease with increasing fluid velocity and even if a discontinuity were originally present it would disappear with time. The fact that only compression shocks are found in media which behave approximately like ideal gases is in agreement with the second law of thermodynamics : (Walker and Taub [5])

It is true of course, that a shock wave is not a discontinuity in the strict sense. It has a finite thickness across which the physical properties change continuously. If this thickness is small compared with some appropriate macroscopic dimension of the flow field, such as the radius of the curvature of a curved shock, the physical relationship may be obtained by an analysis which treats the discontinuity as strict. The assumption that the discontinuity thickness is small is a fundamental one. The term "structure" as applied to a shock wave, refers to the value of physical properties of the fluid within the small but finite thickness of the discontinuity [6]. If the thermodynamic equilibrium in a substance is disturbed, a characteristic time must elapse before equilibrium can be approximately reestablished. If the physical and chemical changes occurring in the discontinuity are sufficiently slow, so that the thickness of the discontinuity is large compared with the characteristic distance, the concept of the thermodynamic quasi - equilibrium may be considered . In this case Navier - Stoke's equations are applicable . If thickness is thin , with physical and chemical

changes occurring rapidly , the essential absence of thermodynamic equilibrium must be taken into account .The first notable concept of shock waves goes almost a century back to Riemann [7],who was the first to recognise the essential difference between infinitely small and finite pressure variations .Theory of shock was later developed by Rankine [8] and Hugniot [9] and many other scholars .In fact shock wave may cause sudden change in aerodynamic behaviour of high speed aircrafts their balance and stability .The problem of shock wave has a bearing on many problems other than those of supersonic aeronautics also . for example , detonation waves.

The concept of magnetohydrodynamic was first introduced by Hoffmann and Taylor [10] ,taking an account of gas dynamic of steller bodies .These magnetohydrodynamic shocks are of great importance in various astrophysical ,geophysical problems and in technological developments for examples , propagation of shocks in steller atmosphere , and discontinuities in magnetoplasma of solarwind , since at very high temperature gases are ionized with high degree of ionization , a mixture of ions and electrons which is called plasma . Since most of the matter in universe is either sufficiently hot or sufficiently diffused that is in the state of plasma. We also know about the presence of cosmic megnetic field, then there is a interaction between hydrodynamic motion field which may result in magnetohydrodynamic shock is of considerable importance not only in various astrophysical and geophysical problems but also in the study of behaviour of interplanetry plasma as well as intersteller masses.

Due to the high temperature there is of interest to consider the effects of thermal radiation in gasdynamic. Sach [11] was first person who derived shock conditions taking into account radiation pressure and radiation energy. Later, Guess and Sen [12], considered the effect of radiative transfer. Marshak [13] took into account radiation flux also and he rederived the Hugoniot shock conditions and similarity solutions. Elliot [14] and Wang [15] considered the similarity solutions of Taylor's expansion problem and Piston problem taking an account of Radiation flux. Bhatnagar and Sachdev [16] studied of the propagation of isothermal shock, they used the Witham's rule to study the variations in the shock strength and shock velocity, after using pressure energy and flux, of radiation. The purpose of present work is to make thorough study of such radiative magneto-hydrodynamic shocks by formulating suitable differential equations and reducing them to the form as to make them amenable for numerical integration.

2. SPHERICAL AND CYLINDRICAL SHOCK

Consider the propagation of a shock wave, through a perfect gas, of great intensity resulting from a strong explosion, i.e. from the instantaneous release of a large quantity of energy.

When the energy is suddenly released, in an infinitely concentrated form and distribution of density pressure etc, depends only on the distance from some point then this is a case of spherical shock.

When the energy is suddenly released along a line and distribution of all quantities is homogeneous in some direction and has complete axial symmetry about that direction, then this is

a case of cylindrical shock.

3. EQUATIONS OF MOTION AND JUMP CONDITION IN MAGNETO ----- HYDRODYNAMICS -----

In an electrically conducting fluids in the presence of magnetic field discontinuity, ie. Shock wave in flow variable can exist's. The study of magnetohydrodynamic shock waves was begun in 1950 with the paper of F.de Hoffmann and Taylor [10] .

When electric current induced in the fluid, then their flow in the magnetic field produces mechanical forces which modify the motion [17], magnetogas dynamic owes its peculiar interest and difficulty to this interaction between the field and the motion. Thus the equations of magnetogasdynamic are the ordinary and electromagnetic equations . We only take into account the interaction between the motion and the magnetic field ,we have ignored the Maxwell's displacement currents. Through out the thesis we take $(\mu) = 1$ because magnetic permeability (μ) differs only slightly from unity which is unimportant. We also assume that the dissipative mechanism such as viscosity, thermal conductivity and electrical resistant are absent.

Since the problems dealt in this thesis relate to magneto gas dynamic or magneto-radiative shocks . We refer in this article the relevant flow and fluid equation [18]

$$P = \rho RT \quad ; \quad (1.1)$$

$$\frac{D\rho}{Dt} + \rho \frac{\partial u}{\partial r} + j \frac{\rho u}{r} = 0 \quad ; \quad (1.2)$$

$$\frac{Du}{Dt} + \frac{1}{\rho} \frac{\partial p}{\partial r} + \frac{h}{\rho} \frac{\partial h}{\partial r} + \frac{Jh^2}{\rho r} = 0 ; \quad (1.3)$$

$$\frac{Dh}{Dt} + u \frac{\partial h}{\partial r} + h \frac{\partial u}{\partial r} + \frac{Jhu}{r} = 0 ; \quad (1.4)$$

$$\frac{\partial}{\partial t} (P \rho^{-\tau}) + u \frac{\partial}{\partial r} (P \rho^{-\tau}) = 0 ; \quad (1.5)$$

where $\frac{D}{Dt} = \frac{\partial}{\partial t} + u \frac{\partial}{\partial r}$

and u, P, ρ, h, r and t are the velocity, pressure, density magnetic field transverse to the flow, radial distance and time respectively, τ is the ratio of specific heat at constant volume and constant pressure. $J=0, 1$ and 2 corresponding to plane, cylindrical and spherical respectively and $V=0$ for plane and $V=1$ corresponds to cylindrical and spherical both.

In the presence of magnetic field, the relation connecting the flow and field quantities on the two sides of the shock surface are as follows [19,20], where the velocity in front the shock wave is zero :

$$h_2 (u-u_2) = h_1 u_1 ;$$

$$p_2 (u-u_2) = p_1 u_1 ;$$

$$p_2 + \frac{1}{2} \rho_2 u^2 + \frac{p_2}{\gamma} = p_1 + \frac{1}{2} \rho_1 u^2 + \frac{p_1}{\gamma};$$

$$\frac{1}{2} (u-u')^2 + \frac{\gamma p_2}{(\gamma-1) \rho_2} + \frac{h^2}{2 \rho_2} = \frac{1}{2} u^2 + \frac{\gamma p_1}{(\gamma-1) \rho_1} + \frac{h^2}{2 \rho_1};$$

where suffix 1 and 2 correspond to the value of the quantities just ahead and just behind the shock surface and u is the shock velocity.

(4) RADIATION PHENOMENON

At very high temperature, the gases become ionized and radiation can be considered as a continuous emission of energy in the form of electromagnetic wave which propagated in the medium with the speed of light. This energy is called radiant or thermal energy radiation. Where as according to quantum theory the radiant energy emitted or absorbed is not continuous, permitting all possible values, as demanded by the wave theory, but in a discrete quantified form, as integral multiples of an elementary quantum of energy, photon or light quanta. The amount of energy in each quanta being given by the product $h\nu$, where h is plank's constant and ν is the frequency of the radiation.

Thus the quantum theory proposes the particles characteristic of radiation, while classical theory the wave characteristics, both being required to understand the complex behaviour of

radiation . A complete study of such a high temperature flow of a gas should consist of the study of gas dynamic field , the electromagnetic field and thermal radiation flux simultaneously . The analysis of simultaneously effects and magnetic field forms the subject matter of radiation magnetohydrodynamics . This theory of thermal radiation can be applied to understand the processes which take place in stellar media , to explain the observed luminosity of stars and nuclear explosions and also to high temperature flow.

Radiative transfer and radiative heat exchange have an influence on both the star and the motion of the fluid . This influence is caused by the fact that fluid loses or gains energy by emitting or absorbing heat . On the flow field of the gas there are three radiation effects expressed in terms of radiation pressure , radiation energy and radiation flux [21 ,22 ,23] .

(a) RADIANT PRESSURE

By the theory of electrodynamic the pressure of a radiation field is equal to one third of radiant energy is

$$P_R = \frac{1}{3} E_R = \frac{1}{3} a_R T^4 ;$$

where T is temperature and a_R is Stefan - Boltz mann constant . This is the only component of the radiation which differs from zero .

(b) RADIATION ENERGY (E.)

The radiant energy density E_R per unit mass of the fluid is

$$E_R = \frac{a T^4}{\rho} ;$$

where ρ is density of fluid

(c) RADIATION FLUX

The net amount of radiant energy passing through the surface per unit area per unit time is called the radiant flux through the surface is gives by

$$F = \frac{C_R}{4} \cdot \frac{a T^4}{\rho} ;$$

$$\text{or } f = D \frac{\text{grad } E}{R}$$

where $D = \frac{CL}{3}$ is the Rosseland diffusion coefficient of

radiation and $L = \frac{1}{R k \rho}$ the Rosseland mean free path of radiation

Magnetic pressure P_h and the magnetic energy E_h are given by

$$P = \frac{h^2}{2P} ;$$

$$E = \frac{h^2}{h \cdot 2p} ;$$

where h is the magnetic field

The fundamental equation of radiation magnetogasdynamics for one dimensional flow are [24]

$$\frac{D\rho}{Dt} + \rho \frac{\partial u}{\partial r} + \rho \frac{u}{r} = 0 ;$$

$$\frac{Du}{Dt} + \frac{1}{\rho} \frac{\partial p}{\partial r} + \frac{h}{\rho} \frac{\partial h}{\partial r} + \frac{\sqrt{h}^2}{\rho r} = 0 ;$$

$$\frac{Dh}{Dt} + u \frac{\partial u}{\partial r} + \frac{\sqrt{h}u}{r} = 0 ;$$

$$\frac{DE}{Dt} + P \frac{D}{Dt} \left(\frac{1}{\rho} \right) + \frac{1}{\rho r} \frac{\partial}{\partial r} (Fr^J) = 0 ;$$

$$\text{where } \frac{D}{Dt} = \left(\frac{\partial}{\partial t} + u \frac{\partial}{\partial r} \right) ;$$

$$\text{where } P = P_m + P_r + P_h ;$$

$$E = E_m + E_R + E_h ;$$

$$E_m = \frac{P_m}{\tau - 1} ;$$

and F is the radiation heat Flux.

where suffixes m , R , h attached to the quantities to expressions for material radiation and magnetic terms respectively .

5. SIMILARITY PRINCIPLE

The fluid is said to be one-dimensional when all its properties depend on only one geometric coordinate and on the time. The spherical, cylindrical and plane waves produce one dimensional motion. The methods of dimensional analysis can be used to find exact solutions of certain problems of one dimensional unsteady motion of a compressible fluid. In the Eulerian approach the basic physical variables are the velocity, u the density ρ and pressure P . The characteristic parameters are the linear coordinate $[r]$, the time t and the constants that enter into the equations, the boundary and the initial conditions of the problem. Since the dimensions of the quantities ρ and P contain the mass, at least one constant a , the dimension of which also contain the mass must be a characteristic parameter. Hence, as in [24] we can assume with out any loss of generality

$$\dim 'a' = \frac{k s}{ML T} ;$$

We can write the velocity, density and pressure as

$$U = \frac{r}{t} V, \quad \rho = \frac{a}{r^{k+3} t^s} G, \quad p = \frac{a}{r^{k+1} t^{s+2}} P :$$

where V, G and P are arbitrary quantities and, therefore, can depend only on one-dimensional combination of r, t and other parameter of the problems. In general, they are functions of two non-dimensional variables. But if an additional characteristic parameter ' b ' can be introduced with dimensions independent of those of ' a '. The number of independent variables which can be formed by combining ' a ' and ' b ' is reduced to one. Since the dimension of the constant ' a ' contains the mass, we can choose the constant ' b ' in a manner, such that its dimension do not contain the mass, that is

$$\dim b = L T ;$$

The single non-dimensional independent variable in this case

will be $\frac{r^m t^n}{b}$, which can be replaced by $m \neq 0$ by the variable

$$\eta = \frac{r}{b^{1/m} t^\sigma} ,$$

$$\text{where } \sigma = -\frac{\eta}{m} ;$$

If $m=0$, V , G and p depend only on the time and the velocity u is proportional to r .

The solutions depending on the independent variables may obtain a number of arbitrary constants.

The above argument shows that when the characteristic parameters include two constant with the independent dimensions in addition to r and t , the partial differential equation satisfied by the velocity, density and pressure in one dimension unsteady motion as a compressible fluid can be replaced by ordinary differential equations for V , G and P . The solutions of these ordinary differential equations can some times be obtained exactly in closed form [25]. For violent spherical explosions in a uniform atmosphere at rest, and in other cases, approximated by using numerical integration [26] such motion are called self similar [27]. The idealized problems of a strong explosion in a homogeneous atmosphere represents a typical example of self-similar flow, in which the flow variables changes with times in such a manner that their distributions with respect to coordinate variable always remain similar in time. The self similar problem of a strong explosion was formulated and solved by Sedov [28] using a brilliant method, which employed the energy integral. Sedov, succeeded in finding an exact analytic solution to the equation of self-similar motion. The same problem was also considered by Taylor [26] who formulated the equation for the problem obtained numerical but not analytic solutions.

(9) CHARACTERISTIC METHOD

Many physical problems lead to the formulation of a quasi-linear system of first order equations, such equations are

linear in first derivatives of the dependent variables, but the coefficient may be functions of the dependent variable when these equations describe wave motion, a good understanding of many of the issues can be developed from the study of plane waves. Accordingly, we start with the case of two independent variables. The two variables often the time and space variable so we denote them by t and x , and use corresponding terminology, but the discussion applies to any variable system if the dependent variables are $U_i(x,t)$ $i=1,2,\dots,n$, the general quasi-linear first order system is

$$A_{ij} \frac{\partial u_j}{\partial t} + a_{ij} \frac{\partial u_j}{\partial x} + b_i = 0, \quad (1.1)$$

where the matrices A, a and vector b may be functions of $v_j \dots v_n$ as well as x and t .

In general, any one of the equations has different combination of $\partial u_j / \partial t$ and $\partial u_j / \partial x$ for u_j . That is it couples information about the rate of change of the different u_j in different directions.

One can not deduce information about the increments of all the u_j for a step in any single direction but we are at liberty to manipulate the n equal to see whether this information can be obtained from some combination of them we therefore consider the linear combination

$$l_i \left(A_{ij} \frac{\partial u_j}{\partial t} + a_{ij} \frac{\partial u_j}{\partial x} \right) + l_i b_i = 0, \quad (1.2)$$

where the vector l is a function of x, t, u and investigate whether l can be chosen so that (1.2) takes the form

$$m_j \left(\beta \frac{\partial u_j}{\partial t} + \frac{\partial u_j}{\partial x} \right) + l_j b_j = 0, \quad (1.3)$$

If this is possible (1.3) provides a relation between the directional derivative of all the u_j in the single direction (α, β) . When this is the case, it will be valuable to introduce curves in the (x, t) plane defined by the vector field (α, β) . If $x = x(n)$, $t = T(n)$ in the parametric representation, of a typical member of this family, the total derivation of u_j on the curve is

$$\frac{du_j}{dn} = T' \frac{\partial u_j}{\partial t} + x' \frac{\partial u_j}{\partial x},$$

without loss of generality, we may take

$$\alpha = x'(n), \beta = T'(n)$$

and writ (1.3) as

$$m \frac{du_j}{dn} + \frac{1}{j} b_j = 0 \quad (1.4)$$

The condition for (1.2) to be in the form (1.4) are

$$\frac{1}{i} A_{ij} = m \frac{T'_j}{j}, \quad \frac{1}{i} a_{ij} = m \frac{x'_j}{j}$$

and we may eliminate the m to give

$$\frac{1}{i} [A_{ij} x'_j - a_{ij} T'_j] = 0, \quad (1.5)$$

There are n equations for the multipliers $\frac{1}{i}$ and the direction (x'_j, T'_j) . Since they are homogeneous in the $\frac{1}{i}$, a necessary and sufficient condition for a nontrivial solution is that the determinant

$$\begin{vmatrix} A_{ij} x'_j - a_{ij} T'_j \end{vmatrix} = 0, \quad (1.6)$$

This is a condition on the direction of the curve such a curve is said to be a characteristic and the corresponding equation (1.4) is said to be in characteristic form.

(10) ARTIFICIAL VISCOSITY

The propagation of strong shock waves in half space due to a surface explosion or impact, has been treated in many levels of approximation. In one of these an attempt is made to account for the material strength by including a Newtonian viscosity term. This approximation seems to have been originated by S.W. vuan and various co-workers [29]. Who have further approximated the solution of the resulting equation by seeking a variety of quasi-similar solutions. In all of these solutions the viscosity coefficient is taken to be at most a function of time but independent of space coordinates. In addition, the flow field in the half space is represented as though it were one half of spherically symmetric flow. The predictions of this theory for certain quantities on the symmetry axis at the shock front are then compared with experiment and it is usually claimed that the agreement constitutes a validation of the model used. However it has been pointed out repeatedly that quantities at the shock front are very insensitive to details of model and can be approximated fairly well by any number of approximations. A recent illustration of this fact is presented in a paper by Billingsley [30] whose result shows that experimental data was incapable of resolving the difference between a wide variety of theoretical treatments even in the subset of quasi-similar solutions with out viscosity. These are many remaining questions about the effects of the spherical flow assumption. The neglect of non-similarities due to non-zero projectile size, and the

approximation used in defining the equation of state to mention only a few. These have been critically reviewed in a recent survey paper by Rae [31] when a spherically symmetric magnetic field is added to this formulation along with a Newtonian viscosity term. The above paper proposes to study the composite effect of all the approximation.

Von-Neumann and Richtmyer [32] developed a new technique of artificial viscosity and introduced an additional term in the following form

$$q = \frac{1}{2} \left(\rho_0 C \Delta x^2 \left(\left| \frac{\partial v}{\partial t} \right| - \frac{\partial v}{\partial t} \right) \right),$$

where C is a dimensionless Constant, v the material velocity x the internal length and ρ_0 the density at $t=0$. We have shown in this thesis that artificial viscosity can smear out shock discontinuity in a magnetized medium more easily than in ordinary gas dynamics.

(11) WITHAM'S RULE

Chester [33] has studied the motion of a shock wave down a non uniform tube on the basis of a linearized theory in which the changes in the tube area and the consequent changes in shock strength have been assumed to be small. In this linearized theory, the solution breaks down when the flow behind the shock wave is nearly sonic. Chisnel [34] and Witham [20] have shown that Chester's work could be simplified and extended one minor simplification is that where as the Chester worked with the full

three dimensional equations and performed an averaging process in the course of his analysis. It is sufficient to work from the outset with the one dimensional formulation. Witham has shown that the motion of the shock can be found in a simple way without solving the equations for the flow behind the shock in detail. This method can be given as the following rule.

The relevant equations of motions are first written in characteristic form. Then the rule is to apply the differential relation which must be satisfied by the flow quantities along a characteristic to the flow quantities just behind the shock wave. Together with the shock relations which express these values in terms of the shock strength, the rule determines the change in the shock strength. In fact it is found to be accurate even when the total changes in the shock strength are not small although a full understanding of this fact is still lacking.

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CHAPTER - II

MAGNETO - RADIATIVE SHOCK WAVE PROPAGATION IN A CONDUCTING PLASMA

1. INTRODUCTION

The problem of propagation of shock wave in a non homogeneous medium has been studied by many authors where the effect of explosion in the stars and atmosphere of the earth are discussed .

The solutions of cylindrically symmetric flow has been obtained by Lin [1]. Ray [2] has discussed the problems of point and line explosion and found an exact analytic solution . Analytic solution in the three cases of plane , cylindrically symmetrical , Spherically symmetrical flows have also been discussed by Sakurai [3] . Rogers [4] has also studied the similarity solutions for all the three cases in uniform atmosphere . Later on Singh and Vishwakarma [5] have discussed the similarity solutions of the flows behind shock waves in a radiative magnetogasdynamics in which total energy increases with time.

In this chapter the problem of explosion along a line in a gas cloud has been discussed , similarity solutions are developed describing the propagation of a cylindrical and spherical shocks in a non - uniform atmosphere where magnetic effect is observed due to ionization of gases and the problem is solved , taking counter gas pressure and radiation heat flux in to account . The radiation pressure and radiation energy are ignored due to weak ionization of gases . The gas in the undisturbed field is assumed

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to be at rest . We also assume the gas to be grey and opaque and the shock to be transparent and isothermal. The total energy of the explosion is constant . The Runge Kutta method has been used for approximations on computer system DEC 1090 at IIT Kanpur .

(2) SELF - SIMILAR FORMULATION

The fundamental equations of conservation of mass , momentum energy and equation of the magnetic field behind the wave are given as

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial r}(\rho u) + J \frac{\rho u}{r} = 0 , \quad (2.1)$$

$$\frac{\partial}{\partial t}(\rho u) + \frac{\partial}{\partial r}(\rho u^2) + \frac{\partial P}{\partial r} + h \frac{\partial h}{\partial r} + \frac{\sqrt{h}^2}{r} = 0 , \quad (2.2)$$

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial r}(\rho u E) + \frac{\partial}{\partial r}(P u) + \frac{1}{J} \frac{J}{r} (q r^J) = 0 , \quad (2.3)$$

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial r}(u h) + \frac{\sqrt{h} u}{r} = 0 , \quad (2.4)$$

where $J=1,2$ for cylindrical and spherical respectively. and $\sqrt{h}=1$. r is the radial distance from the line of explosion, density ρ , pressure P , radial velocity u heat flux q , time internal energy E , and h is the magnetic field.

field .

For an ideal gas internal energy E is given by

$$E = \frac{P}{(\tau-1)\rho} = \frac{\Gamma T}{(\tau-1)} ; E = E(T), \quad (2.5)$$

where τ is the ratio of two specific heat. Furthermore, the equation of state of the gas is taken to be of the form.

$$P = \Gamma \rho T, \quad (2.6)$$

where Γ is the gas constant.

It is assumed the local thermodynamic equilibrium and taking Rosseland's diffusion approximation (Zelodvich Raizers [6]).

$$q = \frac{-c\mu}{3} \frac{\partial}{\partial r} (\sigma T^4),$$

where T is the absolute temperature $\sigma C^2 / 4$ is the Stefan Boltzmann constant, C is the velocity of light and μ , the mean free path of radiation is a function of density and absolute temperature T .

Following Wang [7]

$$\mu = \mu_0 \rho^\alpha T^\beta, \quad (2.8)$$

where μ_0 , α and β are constants. The disturbance is headed by an isothermal shock surface, hence the condition across it are

$$\rho_1 v = \rho_2 (v - u_2) = m_s, \quad (2.9)$$

$$p_2 - p_1 + \frac{\rho_2 v^2}{2} + \frac{\rho_1 (v - u_2)^2}{2} = m_s u_2, \quad (2.10)$$

$$E_1 + \frac{p_1}{\rho_1} + \frac{1}{2} v^2 + \frac{\rho_1 h_1^2}{2} = E_2 + \frac{p_2}{\rho_2} + \frac{1}{2} (v - u_2)^2 + \frac{\rho_2 h_2^2}{2} - \frac{q_2}{m_s} \quad (2.11)$$

$$h_1 u_1 = h_2 (v - u_2), \quad (2.12)$$

$$T_2 = T_1, \quad (2.13)$$

where subscripts 1 and 2 are for the regions just outside and just inside shock surface respectively. v denotes the shock velocity and m_s be the mass flux per unit area across the shock.

(3) SOLUTIONS OF THE EQUATIONS

In front of shock in the undisturbed gaseous medium, the density, pressure and magnetic field distribution are

$$\rho_1 = AR^W, \quad -2 < W < 0 \quad (3.1)$$

$$P_1 = BR^n, \quad n < 0 \quad (3.2)$$

$$h_1 = DR^m, \quad m < 0 \quad (3.3)$$

where R is the shock radius at the time t ; A , W , B , n , D and M_0 are constant.

The similarity variables which reduces the equation governing the flow to ordinary differential equation is taken as

$$\eta = r^a t^b, \quad (3.4)$$

where a and b are constant. It is assumed that the flow is headed by a shock front given by

$$\eta = \eta_0,$$

the other transformation for the flow variables are

$$u = \frac{r}{t} v(\eta) \quad , \quad (3.5)$$

$$p = r^k t^\lambda \Omega(\eta) \quad , \quad (3.6)$$

$$P = r^{k+2} t^{\lambda-2} P(\eta) \quad , \quad (3.7)$$

$$h = r^{\frac{(k+2)}{2}} t^{\frac{(\lambda-2)}{2}} H(\eta) \quad , \quad (3.8)$$

$$q = r^{k+3} t^{\lambda-3} F(\eta) \quad , \quad (3.9)$$

where $\eta = r^a t^b$,

The total energy of the disturbance perunit length is

$$Q = 2\pi J \int_0^R \left[\frac{1}{2} p u^2 + \frac{P}{(\tau-1)} + \frac{h^2}{2} \right] r dr \quad , \quad (3.10)$$

In terms of variable Π we have

$$Q = \frac{2\pi J}{a} \int_0^{\Pi_0} \left[\frac{1}{2} \Omega(\Pi) V^2 + \frac{P}{(\tau - 1)} + H(\Pi) \right]$$

$$* \Pi^{\frac{(k+4)}{a-1}} \frac{1}{t} \left[\lambda - 2 - \frac{a}{b} (k+4) \right] * d\Pi, \quad (3.11)$$

where Π_0 is the value of Π at the shock front

$$\Pi = \epsilon t^\mu, \quad 0 < \mu = 1$$

where shock surface to be given by $\Pi = \text{constant}$. This fixes the

velocity of the shock surface as

$$V = \frac{\mu - b}{a} \frac{R}{t}, \quad (3.12)$$

which represents an out going surface if $a < 1$. The total energy of disturbance within the shock surface at any time t is constant. This by (3.11) requires that

$$\lambda - 2 - \frac{a}{b} (k+4) = 0. \quad (3.13)$$

Let the Mach and Alfvén Mach number's at the shock front respectively be defined by

$$M^2 = \frac{v^2 \rho_1}{\tau p_1},$$

$$M_A^2 = \frac{v^2 \rho_1}{\tau h_1^2} \quad (3.14)$$

By direct substitution of (3.5) - (3.9) in the equation of motion (2.1) - (2.8) shock condition (2.9) - (2.13) and after utilising relation (3.13), we find the similarity condition, following Singh and the Vishwakarma [5] are compatible when

$$k=w, \quad a=0, \quad a=-(4+w), \quad b=2, \quad n=-2, \quad (3.15)$$

$$\text{and } m = \frac{w+2}{2}, \quad \beta = \frac{-5}{2}, \quad \alpha = \frac{w+1}{w}.$$

Hence pressure distribution becomes

$$P_1 = BR^{-2}, \quad (3.16)$$

and equation (2.1) - (2.4) and (2.7) are now transformed into the forms .

$$\frac{\Omega'(\pi)}{\Omega(\pi)} = \frac{(4+W)\pi V'(\pi) - (W+1+J)V(\pi)}{[2 - (4+W)V(\pi)]\pi}, \quad (3.17)$$

$$\frac{P'(\pi)}{P(\pi)} = \frac{\Omega(\pi)}{p(\pi)} \frac{[\pi V'(\pi) \{2 - (4+W)V(\pi)\} + V(\pi) \{V(\pi)(1-J)-1\}]}{\pi(4+W)}$$

$$+ \frac{H^2(\pi) [(2\sqrt{J} - 2) - \pi(4+W)^2 V'(\pi)]}{\pi[4+W][2 - (4+W)V(\pi)]} + \frac{(W+2)}{\pi(4+W)}, \quad (3.18)$$

$$\frac{F'(\pi)}{F(\pi)} = \frac{P(\pi)}{F(\pi)} \frac{[\tau(3+W)V(\pi) - (4+W)\tau\pi V'(\pi) - 2]}{\pi[\tau-1](4+W)},$$

$$+ \frac{P'(\pi)}{F(\pi)} \frac{[2 - (4+W)\tau V(\pi)]}{(\tau-1)(4+W)} + \frac{(W+J+3)}{\pi(4+W)}, \quad (3.19)$$

$$\frac{F(\pi)}{P(\pi)} = - \frac{N (P(\pi)/A)^{1/2}}{(\Omega(\pi)/A)^{3/2-\alpha}} \frac{[2 - (4+W)\pi \{-\frac{P'(\pi)}{P(\pi)} - \frac{\Omega'(\pi)}{\Omega(\pi)}\}]}{(\Omega(\pi)/A)} \quad (3.20)$$

where $N = \frac{4\sigma C\mu}{3\Gamma^{3/2} A^{1-\alpha}} = \text{a non dimensionaal parameter} \quad (3.21)$

$$\frac{H'(\eta)}{H(\eta)} = \frac{n[4+w] V'(\eta) - (w/2 + \frac{1}{2} + 2) V(\eta) + 1}{n[2 - (4+w) V'(\eta)]} \quad (3.22)$$

$$V'(\eta) = \frac{1}{N} \frac{(F(\eta)/A) (Q(\eta)/A)^{\frac{1}{2}-\alpha} [2 - (4+w) V(\eta)]}{[P(\eta)/A]^{\frac{1}{2}} n[2 - (4+w) V'(\eta)]^{\frac{1}{2}} (4+w)^2 [H^2(\eta) + 1] \frac{P(\eta)}{Q(\eta)}}$$

$$\frac{P(\eta)}{Q(\eta)} = \frac{[2w + 2(\tau-1)H^2(\eta) - (J+1)(4+w)V(\eta)]}{n[2 - (4+w)V'(\eta)]^{\frac{1}{2}} (4+w)^2 [H^2(\eta) + 1] \frac{P(\eta)}{Q(\eta)}} \quad (3.23)$$

The approximate shock condition are

$$V(\eta)_0 = \frac{2}{(4+w)} \left[1 - \frac{1}{\tau M^2} - \frac{1}{\tau M^2} \right] \quad (3.25)$$

$$Q(\eta)_0 = \frac{\tau M^2 M^2}{(M^2 + M^2)} \quad (3.26)$$

$$F(\pi)_0 = \frac{4}{(4+W)} \frac{\frac{M^2}{A}}{\left(\frac{M^2}{A} + \frac{M^2}{A}\right)}, \quad (3.27)$$

$$F(\pi)_0 = \frac{-4}{(4+W)} \left(\frac{\frac{M^2}{A} + \frac{M^2}{A}}{\left[\tau \frac{M^4}{A} + \frac{M^4}{A}\right]} - 1 \right), \quad (3.28)$$

$$H(\pi)_0 = \frac{4}{(4+W)^2} \left[\frac{3}{(\tau M)^2} + \frac{\frac{2\tau M^4}{A}}{\tau M \left(\frac{M^2}{A} + \frac{M^2}{A}\right)} \right], \quad (3.29)$$

when $\pi_0 = 1$

(4) RESULTS AND DISCUSSION

For exhibiting the numerical solution it is convenient to write the flow and field variables in the following non-dimensional forms

$$\frac{U}{U_2} = \frac{\frac{1}{(4+W)} \pi_0}{\pi_0} \quad \frac{V(\pi)}{V(\pi)_0}, \quad (4.1)$$

$$w/(4+w)$$

$$\frac{p}{p_1} = \frac{\binom{n}{0}}{\binom{n}{1}} \frac{\Omega(n)}{\Omega(n)}, \quad (4.2)$$

$$\frac{P}{P_2} = \frac{\binom{n}{0}}{\binom{n}{2}} \frac{P(n)}{P(n)}, \quad (4.3)$$

$$\frac{q}{q_2} = \frac{\binom{n}{0}}{\binom{n}{2}} \frac{F(n)}{F(n)}, \quad (4.4)$$

$$\frac{h}{h_2} = \frac{\binom{n}{0}}{\binom{n}{2}} \frac{H(n)}{H(n)}, \quad (4.5)$$

Numerical results for certain choice of parameter are reproduced in a graphical forms. Calculations are made for following value of parameters.

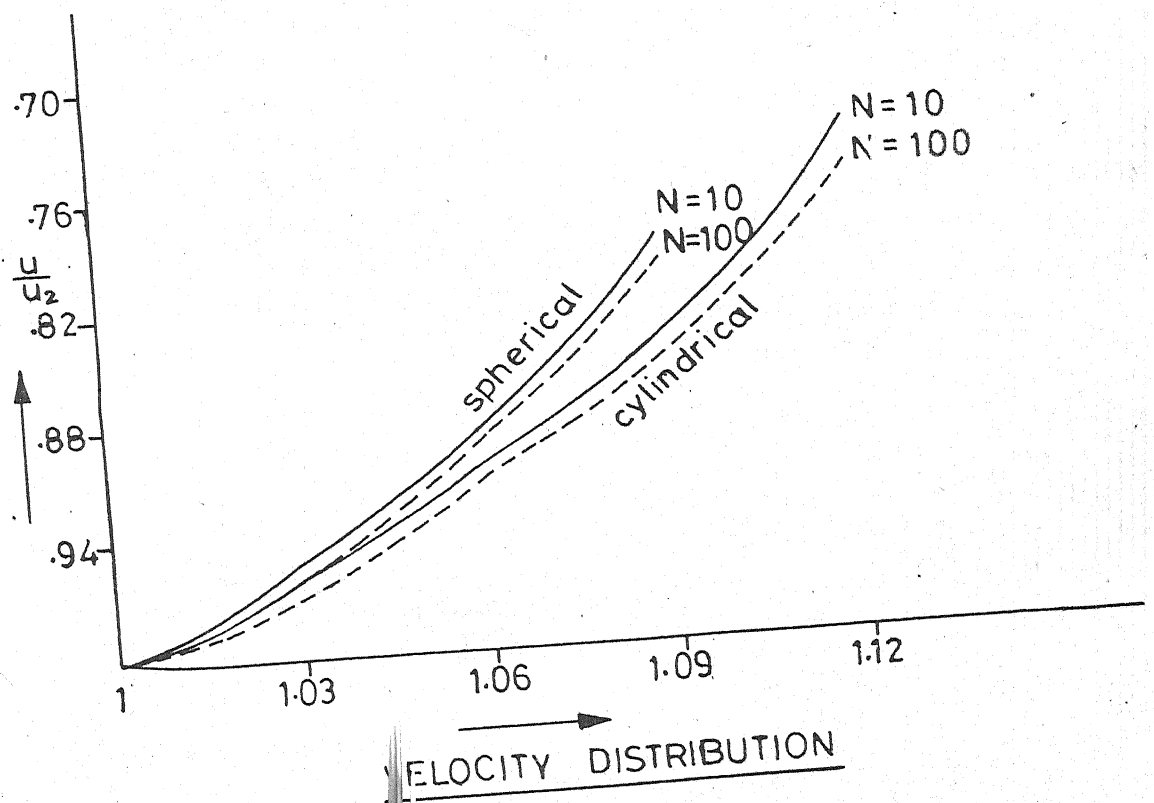
$$(i) \tau=4/3, M=20, M_A^2=30, W=-1.5, \alpha=1/3, J=1, N=10, \hat{V}=1$$

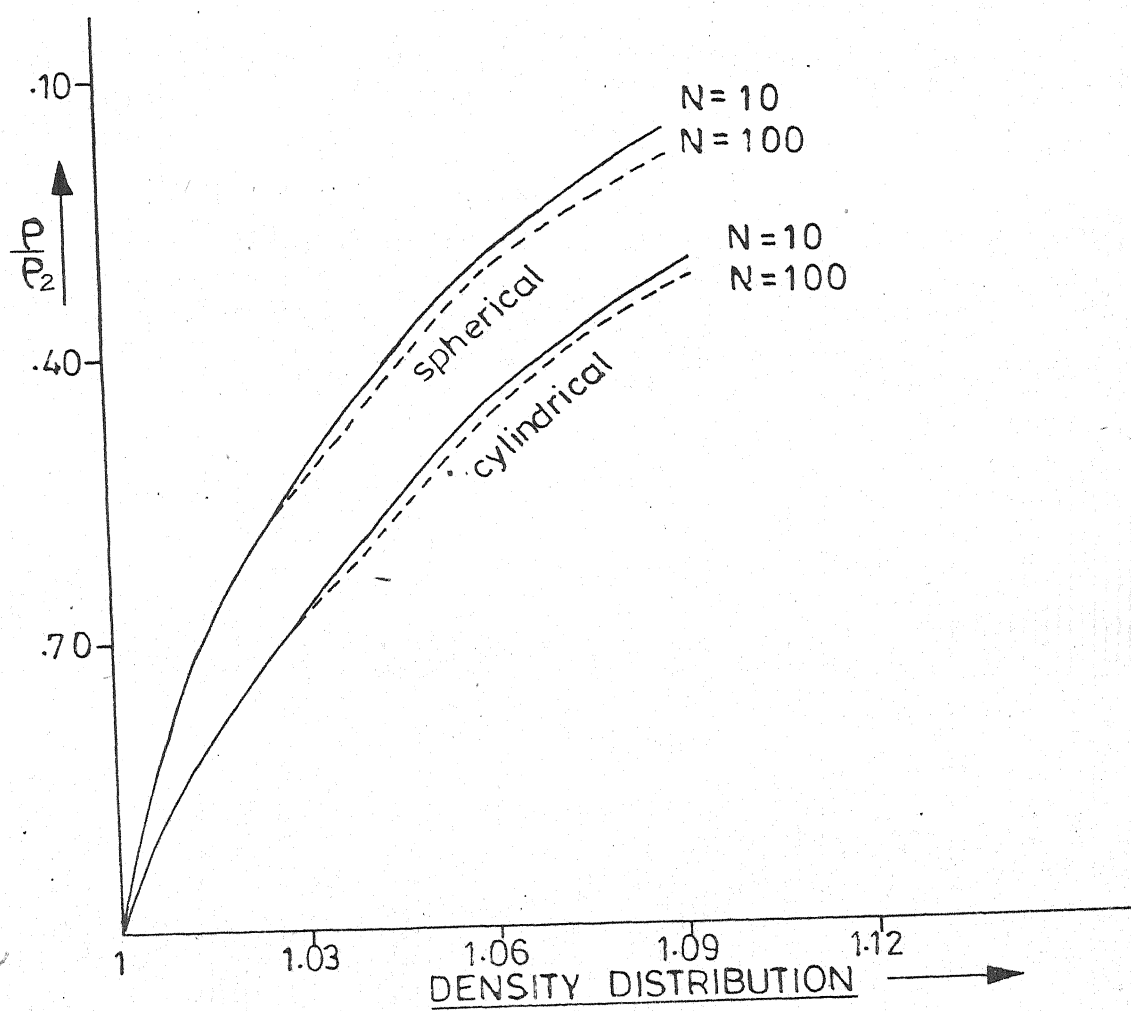
$$(ii) \tau=4/3, M=20, M_A^2=30, W=-1.5, \alpha=1/3, J=1, \hat{V}=1, J=1, N=100$$

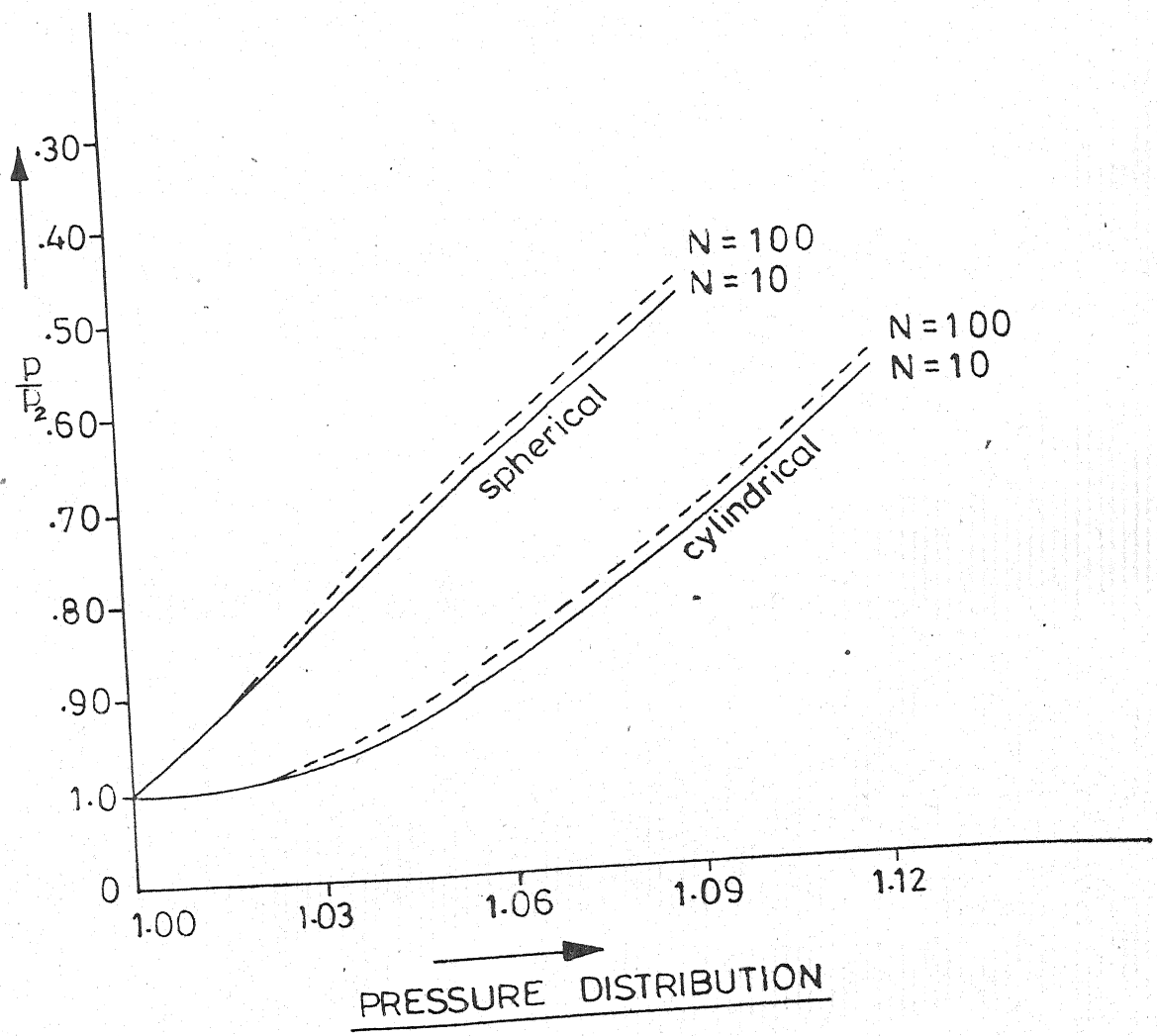
$$(iii) \tau=4/3, M^2=20, M_A^2=30, W=-1.5, \alpha=1/3, J=2, V=1, N=10$$

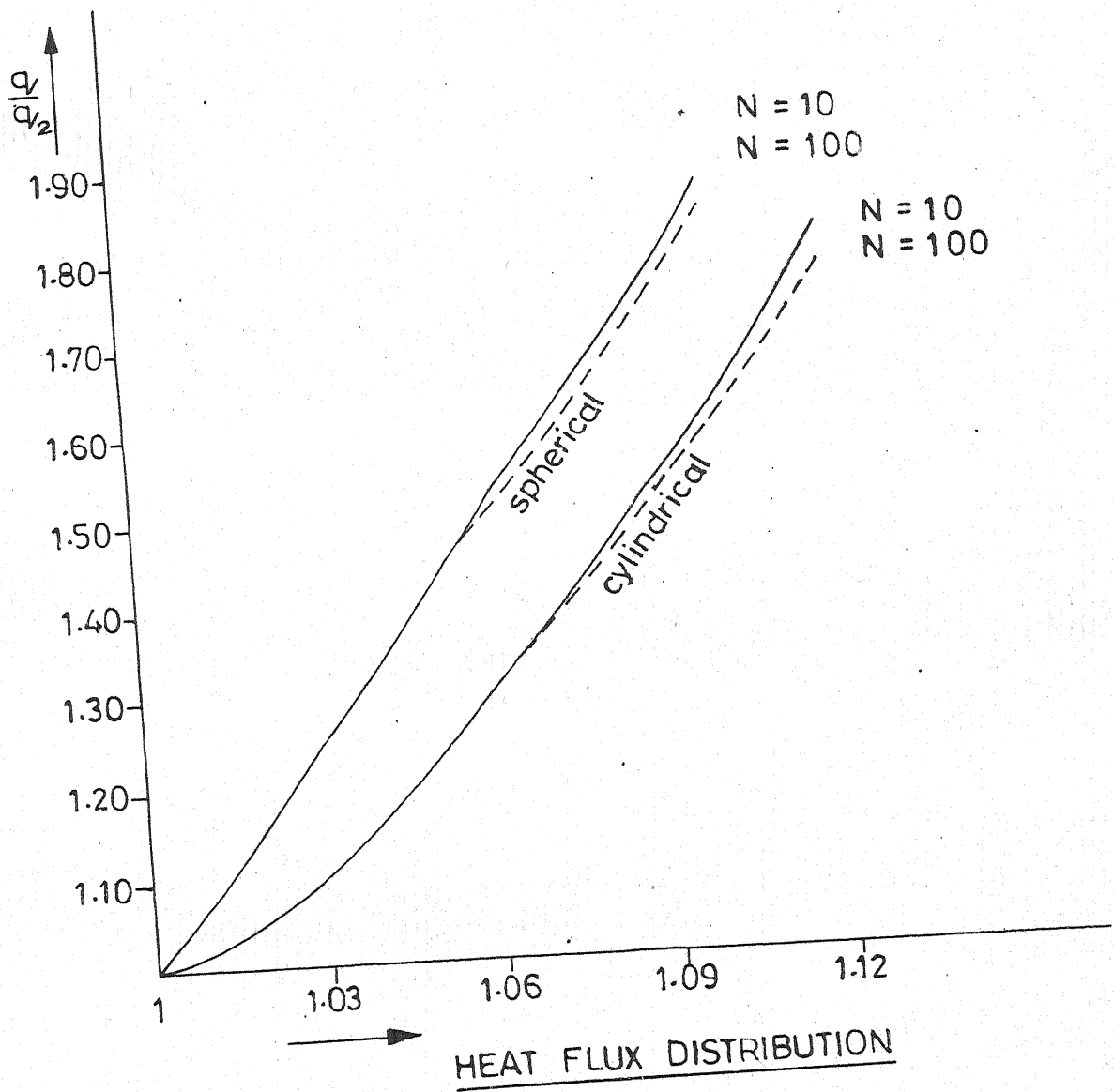
$$(iv) \tau=4/3, M^2=20, M_A^2=30, W=-1.5, \alpha=1/3, J=2, V=1, N=100$$

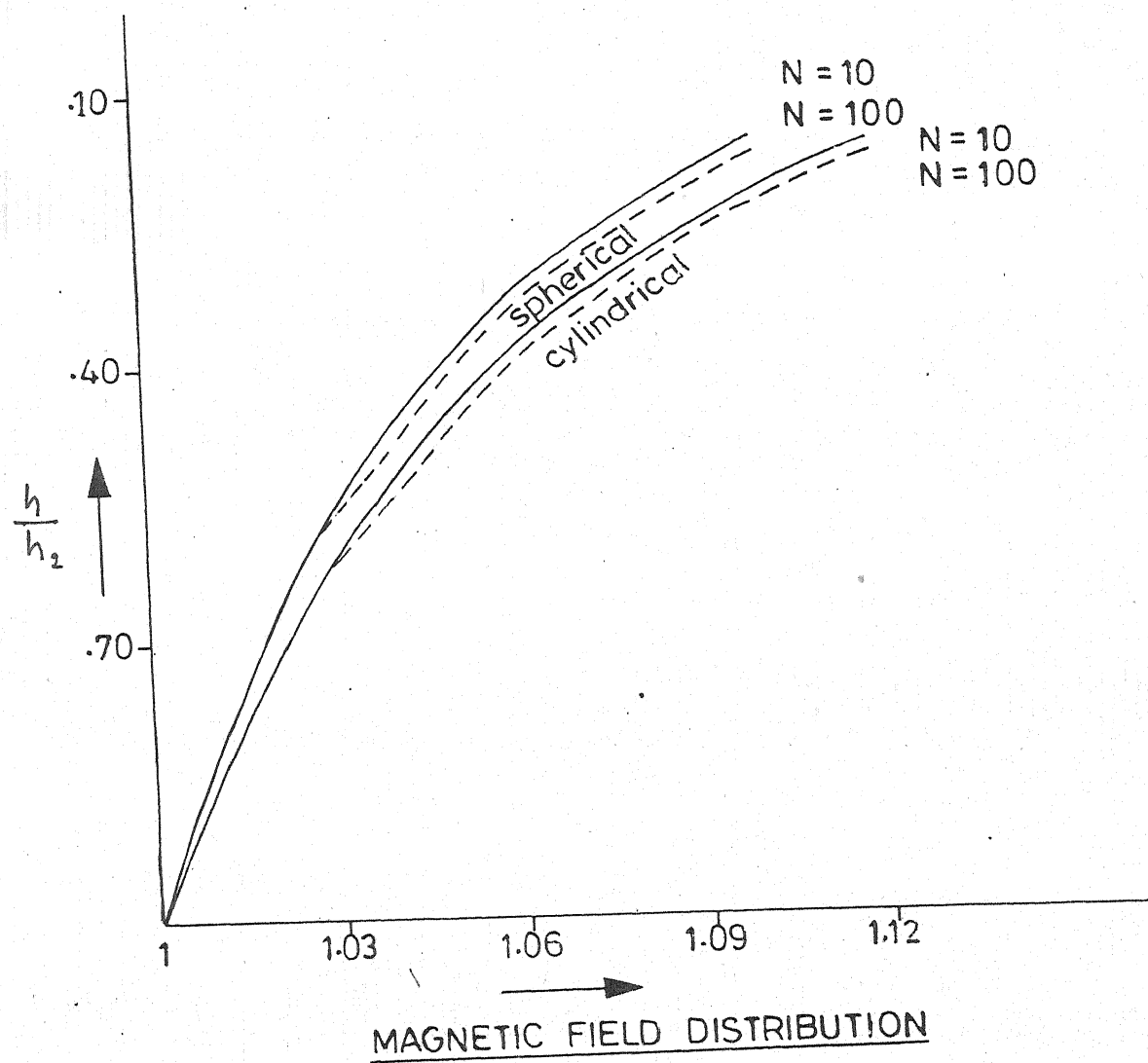
From the graphs it is clear that the velocity, density, pressure, magnetic field distribution and heat flux are maximum at the shock front and decrease more rapidly towards the line of explosion as the value of η increases and there is also slight change in these variables with the change of radiation parameter. Through the graphs it is also clear that decrease in velocity, density, pressure, radiation flux and magnetic field variables is more in spherical case than decrease in cylindrical case.











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CHAPTER III

SELF SIMILAR MAGNETO GAS DYNAMIC CYLINDRICAL SHOCK WAVES

(1) INTRODUCTION

A cylindrical wave of explosion with a shock surface as wave front produced on account of a sudden release of a finite amount of energy, expanding outwards in a conducting gas subjected to a magnetic field has been studied by Pai [1], Christer and Helliwell [2] and many others. Deb Ray [3] and Singh - Vishwakarma [4] have obtained similarity solution for strong cylindrical blast waves in a conducting non uniform medium.

The present chapter deals with the problem of the instantaneous release of energy along a line in a gas cloud thunder in the effect of magnetic field where density varies with time. The motion of a gas is assumed to be adiabatic and total energy of the wave remains constant. A comparison has been made on the effects of the transverse and axial components of the magnetic field variables behind the shock surface. The transverse and axial components of the magnetic field (h_θ and h_z) respectively. The numerical calculation have been done on DEC system 1090 computer by R.K.G.S programme.

(2) EQUATIONS OF MOTION AND BOUNDARY CONDITIONS

Following Witham [5], the equation of motion for one-dimensional unsteady flow of a perfect gas with transverse and axial magnetic field are

$$\frac{\partial P}{\partial t} + u \frac{\partial P}{\partial r} + \rho \frac{\partial u}{\partial r} + \rho \frac{u}{r} = 0, \quad (2.1)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} + \frac{1}{\rho} \left[\frac{\partial P}{\partial r} + \frac{1}{2} \frac{\partial}{\partial r} \left(H_{\theta}^2 \right) + \frac{H_{\theta}^2}{r} \right] = 0, \quad (2.2)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} + \frac{1}{\rho} \left[\frac{\partial P}{\partial r} + \frac{1}{2} \frac{\partial}{\partial r} \left(H_z^2 \right) \right] = 0, \quad (2.3)$$

$$\frac{\partial P}{\partial t} + u \frac{\partial P}{\partial r} - \frac{\tau P}{\rho} \left[\frac{\partial P}{\partial t} + u \frac{\partial P}{\partial r} \right] = 0, \quad (2.4)$$

$$\frac{\partial H_{\theta}}{\partial t} + H_{\theta} \frac{\partial u}{\partial r} + u \frac{\partial H_{\theta}}{\partial r} = 0, \quad (2.5)$$

$$\frac{\partial H_z}{\partial t} + H_z \frac{\partial u}{\partial r} + H_z \frac{u}{r} + u \frac{\partial H_z}{\partial r} = 0, \quad (2.6)$$

where $P, u, \rho, H_{\theta}, H_z$ are pressure, velocity, density, transverse

magnetic field and axial magnetic field. Magnetic field permeability (μ) of the medium is taken to be unity throughout the problem. All are function of r and t . τ is the ratio of specific heats.

Following Witham [5], we find the strong shock boundary conditions to be .

$$p_1 = \frac{\tau+1}{\tau-1} p_0,$$

$$p_1 = \frac{2}{\tau-1} p_0 \frac{z}{R},$$

$$u_1 = \frac{2}{\tau-1} R,$$

(2.7)

$$H_{\theta 1} = \frac{\tau+1}{\tau-1} H_{\theta 0},$$

$$H_{z 1} = \frac{\tau+1}{\tau-1} H_{z 0},$$

where subscripts (1) and (0) denote the regions just inside and just outside the shock front respectively.

(3) SIMILARITY SOLUTIONS

In order to reduce the equations of motion to ordinary differential equation, we now introduce the following similarity transformation. Let the similarity variables η be in the form $\eta = r/R$, $R = R(t)$. (3.1).

The solution of the partial differential equation (2.1) to (2.6), in the form

$$u = R \cdot v(\eta) ,$$

$$p = p_0 g(\eta) ,$$

$$P = p_0 R^2 (\eta) ,$$

$$H_\theta = p_0^{1/2} R h_\theta(\eta) , \quad (3.2)$$

$$H_z = p_0^{1/2} R h_z(\eta) ,$$

where v, g, t, h_θ , and h_z are the function of η . The scales R, p_0 are time independent in some manner yet unknown.

By substituting the relation (3.2) in to equation (2.1) - (2.6), taking account of the definition of similarity variables (3.1) and using of the relation of the type to transform the derivatives

$$\frac{\partial p}{\partial t} = g p_0 - p_0 g' \eta \frac{R}{R} ,$$

$$\frac{\partial p}{\partial r} = p_0 \frac{g}{R} ,$$

(3.3)

$$\frac{\partial H_\theta}{\partial t} = \frac{h_\theta}{p_0} (2 R p_0 + R p_0') - p_0^{1/2} \frac{R^2}{R} \eta h_\theta' = \frac{\partial H_z}{\partial t} ,$$

$$\frac{\partial H}{\partial r} = \rho_0 \frac{\dot{R}}{R} \quad h' = \frac{H}{r} \quad (3.3)$$

The dot represents differentiation of scales with respect to time and prime denote differentiation of functions with respect to similarity variables. After using the relation, differential equation becomes

$$\frac{\rho_0}{\rho_0} + \frac{\dot{R}}{R} [V + (V - n) \frac{\theta'}{\theta} + \frac{V}{\theta}] = 0 \quad (3.4)$$

$$\frac{\dot{R}}{R} \left[\frac{\ddot{R}}{R} + \frac{\dot{\rho}_0}{2\rho_0} \right] + (V - n) \frac{h'}{h} \frac{\theta'}{\theta} + V' = 0 \quad (3.5)$$

$$\frac{\ddot{R}}{R} V + [V - n] V + \frac{1}{\theta} \left(f' + h' \left(\frac{h'}{h} + \frac{\theta'}{\theta} \right) \right) = 0 \quad (3.6)$$

$$\frac{\ddot{R}}{R} V + [V - n] V + \frac{1}{\theta} (f' + h_z' h_z') = 0 \quad (3.7)$$

$$\frac{\dot{R}}{R} \frac{d}{dt} \left[\log R \rho_0^{1-\tau} \right] + (V - n) \left(\frac{f'}{f} - \frac{\theta'}{\theta} \right) = 0 \quad (3.8)$$

In order that similarity solutions (3.2) be meaningful, it is necessary that variable t and η in equation (3.4 - 3.8) must be separable, this possible if

$$\frac{R}{R^2} = \text{constant},$$

$$\text{and } \frac{\rho_0}{\rho_0} = \text{constant} :$$

$$R = At^\alpha, \quad (3.9)$$

$$\rho_0 = Bt^\beta, \quad (3.10)$$

where A , B , α and β are constants. Thus all the scales in the self similar motion have a power law dependence on time. By use of relation (3.9) and (3.10) equations (3.4) - (3.8) take the non dimensional form of ordinary differential equation are as,

$$\frac{\beta}{\alpha} + V + (V - \eta) \frac{\eta'}{\eta} + \frac{V}{\eta} = 0, \quad (3.11)$$

$$\frac{2(\alpha - 1) + \beta}{2\alpha} + (V - \eta) \frac{\eta'}{\eta} + V = 0, \quad (3.12)$$

$$\frac{2(\alpha - 1) + \theta}{2\alpha} + (V - \Pi) \left\{ \frac{h}{h} \frac{z}{z} + V' + \frac{V}{\Pi} \right\} = 0, \quad (3.13)$$

$$\frac{(\alpha-1)}{\alpha} V + (V - \Pi) V + \frac{1}{g} \left\{ f + h \left(\frac{h}{\theta} + \frac{\theta}{g} \right) \right\} = 0, \quad (3.14)$$

$$\frac{(\alpha-1)}{\alpha} V + (V - \Pi) V + \frac{1}{g} \left\{ f + h \frac{h}{z} \right\} = 0, \quad (3.15)$$

$$\frac{2(\alpha-1)+(1-\tau)}{\alpha} + (V - \Pi) \left\{ \frac{f}{f} - \tau \frac{g}{g} \right\} = 0. \quad (3.16)$$

The total energy of the flow as

$$E = 2\pi \int_0^R \frac{1}{2} \rho u^2 + \frac{P}{\tau-1} + \frac{1}{2} \left(H^2 \text{ or } H^2 \right) r dr. \quad (3.17)$$

Equation (3.2), (3.9) and (3.10) reduce the above equation in the form.

$$E = 2\pi B A \alpha t \int_0^R \frac{4}{2} \frac{4\alpha+\theta-2}{2} \frac{1}{2} gV + \frac{f}{\tau-1} + \frac{h^2}{h} \text{ or } \left(\frac{h^2}{h} \right) \Pi d\Pi. \quad (3.18)$$

Since the total energy of the gas is constant so we have

$$\theta = 2 - 4\alpha. \quad (3.19)$$

It is clear from the equation (3.19) that uniform expansion of wave takes place when $\theta = -2$. The solution have their physical significance only when $-2 \leq \theta \leq 0$

After using similarity transformation (3.2) the jump condition (2.7) becomes

$$g(1) = \frac{\tau+1}{\tau-1} ,$$

$$f(1) = \frac{2}{\tau+1} , \quad (3.20)$$

$$h(1) = M_A^{-1} \frac{\tau+1}{\tau-1} ,$$

where M_A is the Alfvén Mach numbers $M_A = \frac{1}{2} \frac{\dot{R}}{H_0}$

(4) RESULT AND DISCUSSION

The calculation of results have been obtained in the following non dimensional form

$$\frac{u}{u_1} = \frac{\tau+1}{2} u(\eta) , \quad (4.1)$$

$$\frac{\rho}{\rho_1} = \frac{\tau-1}{\tau+1} g(\eta) , \quad (4.2)$$

$$\frac{P}{P_1} = \frac{\tau+1}{2} f(\eta) \quad , \quad (4.3)$$

$$\frac{H}{H_{\theta 1}} = \frac{\tau-1}{\tau+1} M \frac{h(\eta)}{A \theta} \quad , \quad (4.4)$$

$$\frac{H}{H_{z 1}} = \frac{\tau-1}{\tau+1} M \frac{h(\eta)}{A} \quad . \quad (4.5)$$

Numerical result for certain choices of parameters are reproduced in the form of graphical form . The calculation of the result are for following values of parameters .

$$(i) \quad \tau=1.4 \quad , \quad \alpha=0.25 \quad , \quad M=10 \quad , \quad \beta=1$$

A

$$(ii) \quad \tau=1.4 \quad , \quad \alpha=0.25 \quad , \quad M=10 \quad , \quad \beta=0$$

A

In this problem, for the shock which is produced by a line explosion moves in conducting gas, we have discussed two cases and makes a comparison between them . .

Case I

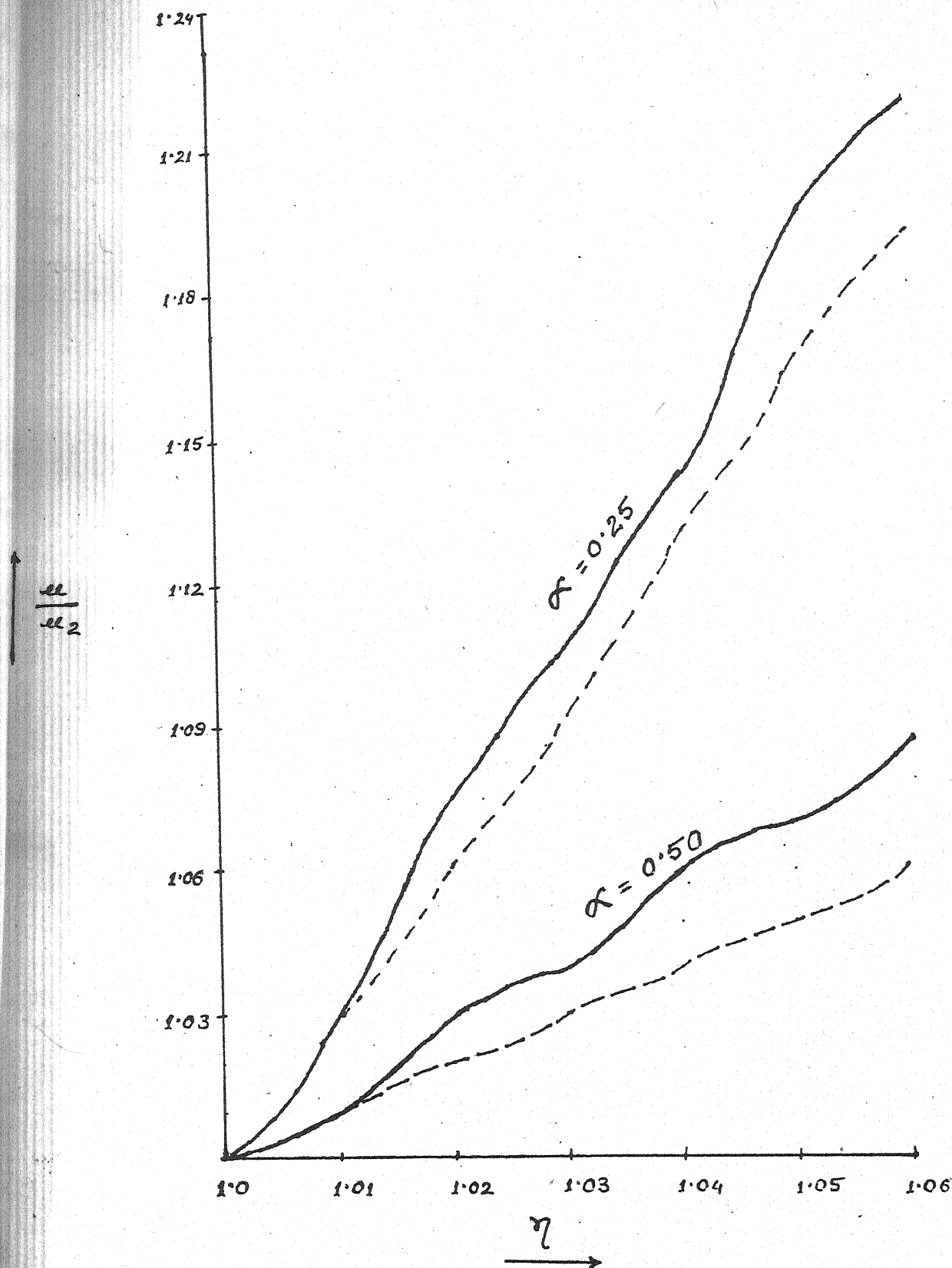
Propagation of cylindrical shock wave with azimuthal magnetic axial field .

Case II

Propagation of cylindrical shock wave with transverse magnetic field .

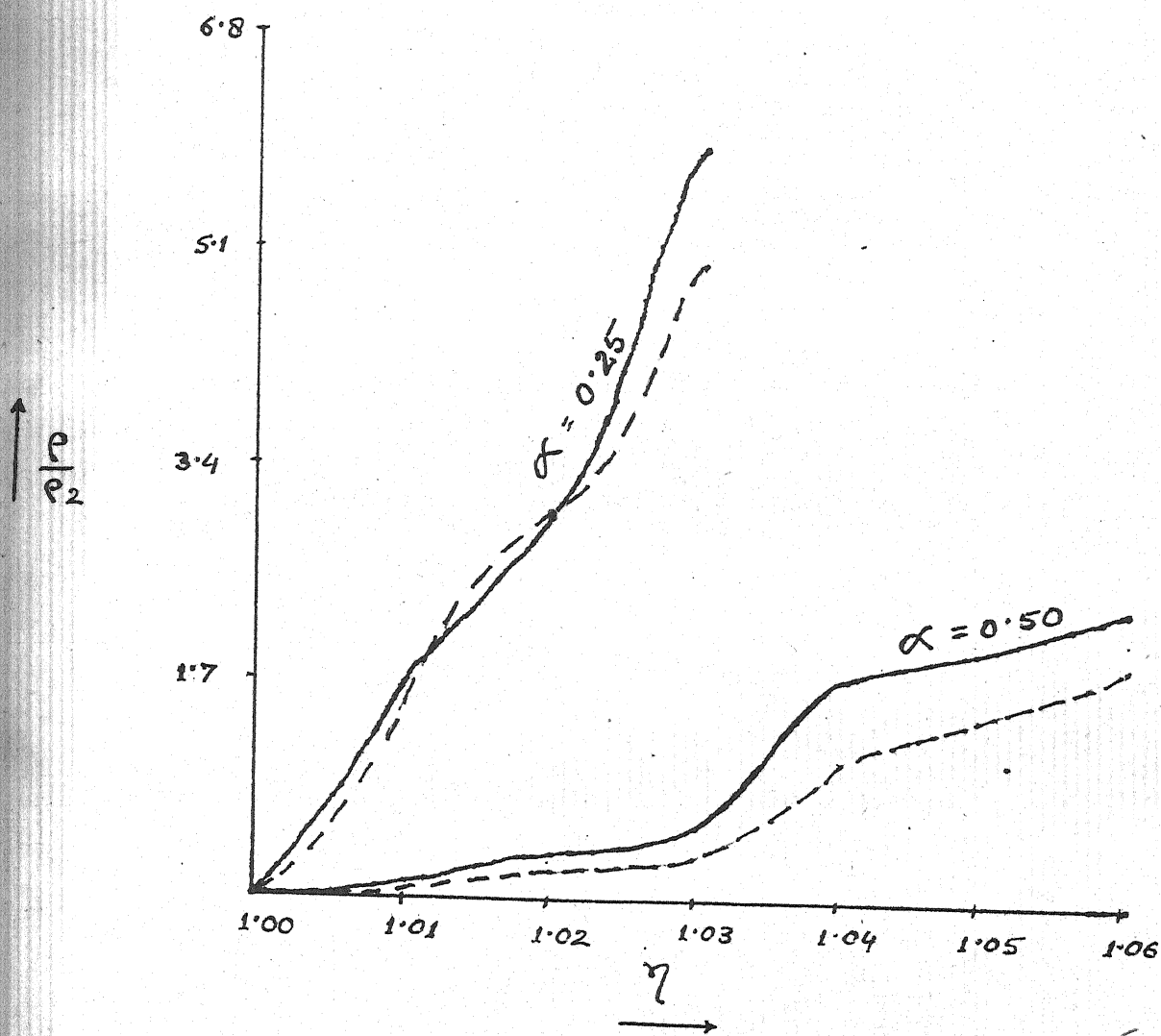
A comparision has also been made for both the above cases . It is observed that when the shock radius is contrating that is $\alpha = .25$, ther is sharp increase in velocity , density, pressure and magnetic feild of the fluid particles behind the shock surface as compared to $\alpha = .50$, when the contraction into shock radius is less .

—— WITH AZIMUTHAL MAGNETIC FIELD
----- TRANSVERSE MAGNETIC FIELD

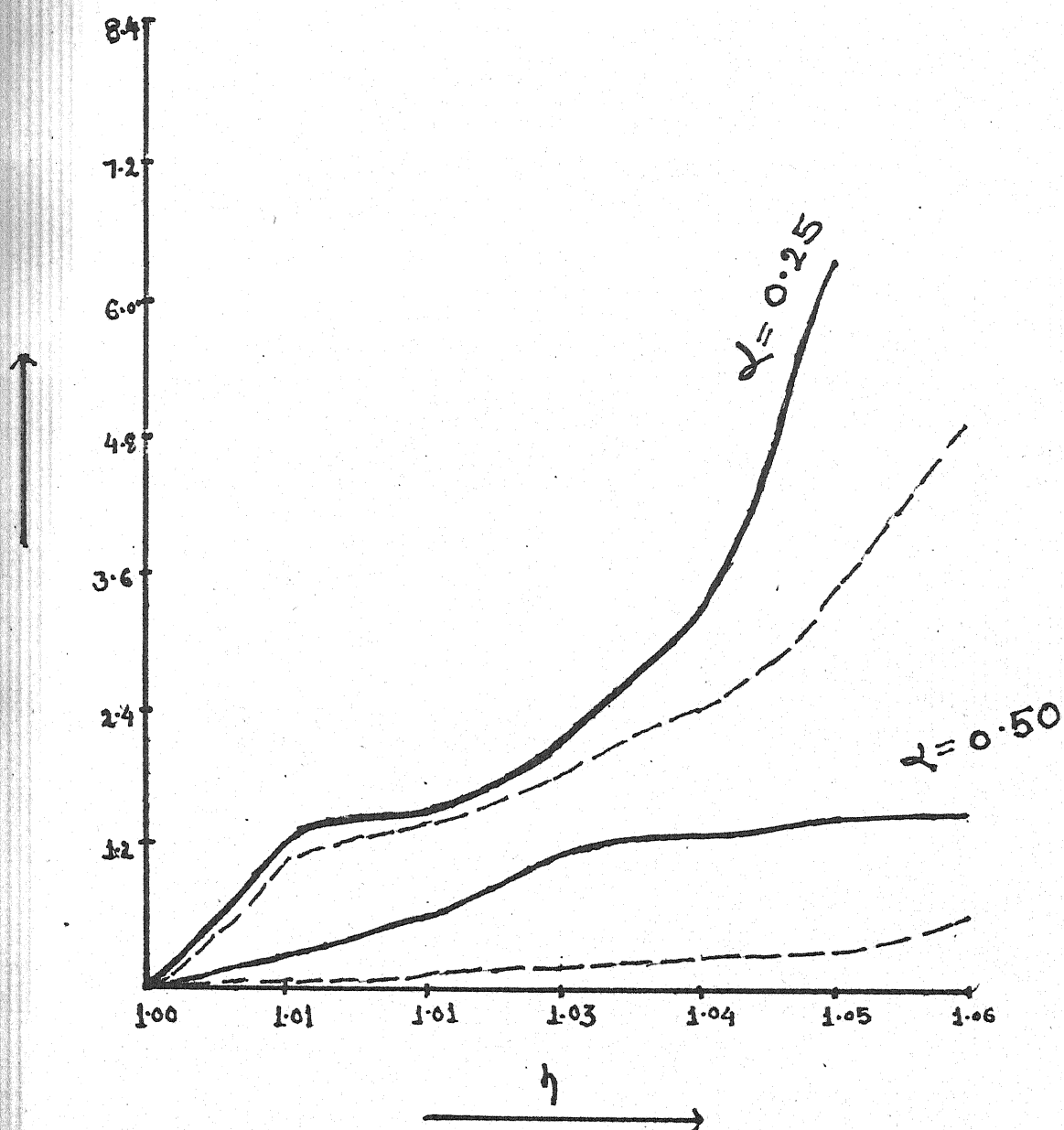


VELOCITY DISTRIBUTION

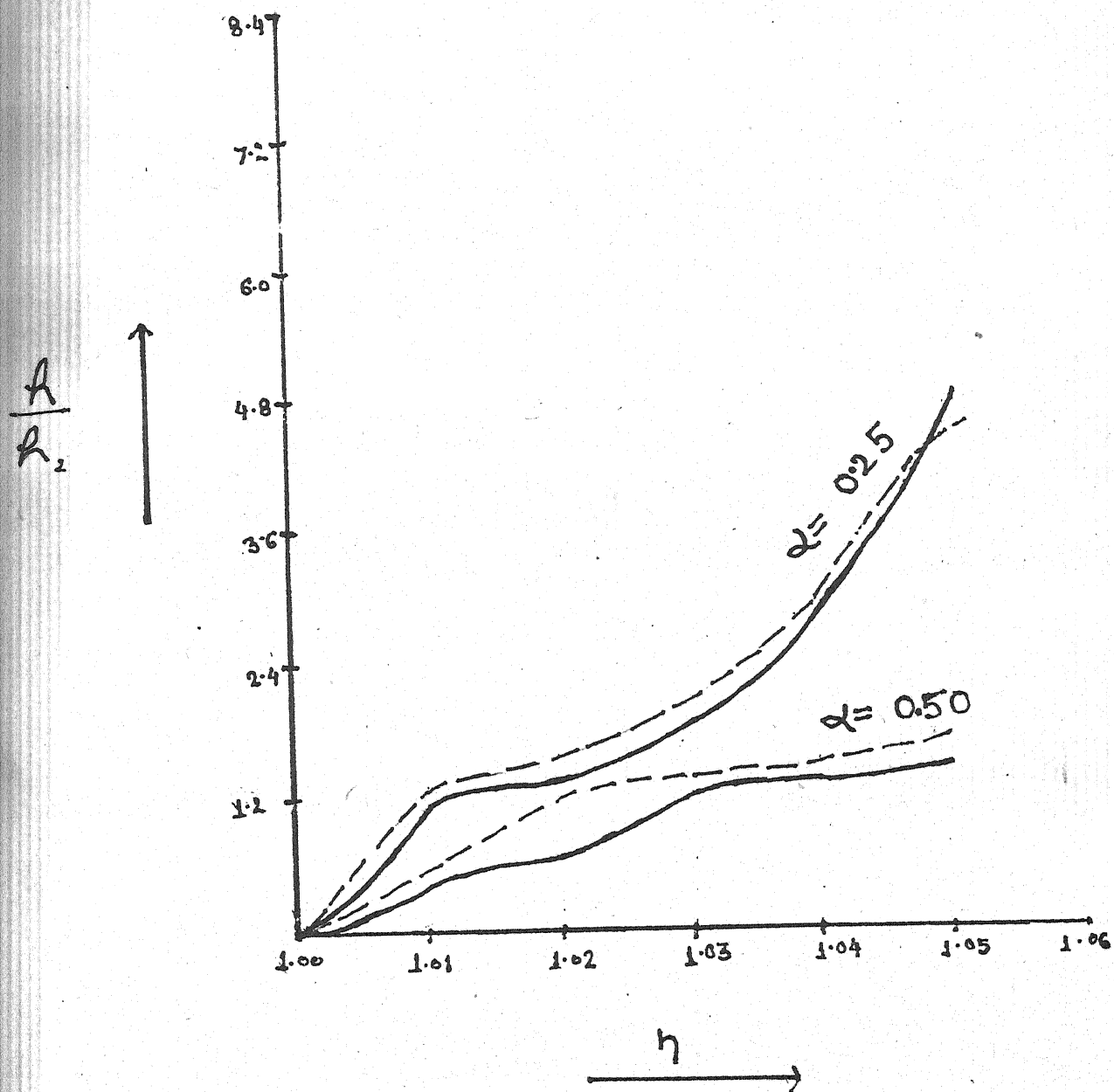
η



DENSITY DISTRIBUTION
 $1(B)$



PRESSURE DISTRIBUTION



MAGNETIC FIELD DISTRIBUTION

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CHAPTER IV

PROPAGATION OF SPHERICALLY SYMMETRICAL DISCONTINUITIES WITH INCREASING ENERGY IN GENERALIZED ROCHE MODEL

(1) INTRODUCTION

In the earlier investigation, the self-similar solution driven out by a sudden point explosion of core of the generalized Roche model are investigated by Carrus et al [1]. Rogers [2] has discussed methods for obtaining analytical solution of the same problem. Runga Rao and Purohit [3] has studied the self similar isothermal flow in generalized Roche model. Roseenau [4] has attempted the self similar adiabatic flow behind spherical shock wave in the presence of magnetic field. One of the basic assumption of their work is that the total energy contain behind the shockfront is constant. Deb Ray [5] has reviewed the Roche model and obtained the exact non similarity solution taking total energy of the wave non constant.

In this chapter, the similarity solution in the Generalized Roche model has been developed, when the radiation heat flux is more important than the radiation pressure and radiation energy. The effect of magnetic field has also taken into account. The unsteady model of Roche consists of a gas distributed with spherical symmetry around a nucleus having a large mass (m). It is assumed that the gravitating effect of gas itself can be neglected compared with the attraction of heavy nucleus.

(2) EQUATION OF MOTION AND BOUNDARY CONDITIONS

The equation of continuity momentum, field and energy in the Generalized Roche model are .

$$\frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial r} + \rho \frac{\partial u}{\partial r} + \frac{\rho u}{r} = 0 \quad (2.1)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} + \frac{1}{\rho} \frac{\partial P}{\partial r} + \frac{1}{2} \frac{\partial}{\partial r} (h^2) + \frac{1}{\rho} \frac{h^2}{r} + \frac{Gm}{r^2} = 0 \quad (2.2)$$

$$\frac{\partial h}{\partial t} + u \frac{\partial h}{\partial r} + h \frac{\partial u}{\partial r} = 0 \quad (2.3)$$

$$\frac{\partial P}{\partial t} + u \frac{\partial P}{\partial r} - \frac{\tau P}{\rho} \left(\frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial r} \right) + (\tau-1) \frac{1}{r} \frac{\partial}{\partial r} (r.F) = 0 \quad (2.4)$$

where u, P, ρ, h and F are the velocity, pressure, density, magnetic field and radiation heat flux, at radial distance (r) from the centre of core at time (t); G be the gravitational constant. The magnetic permeability of the medium has taken to be unity through out the problems. The equation of state for ideal gas is given by

$$P = \Gamma \rho T \quad (2.5)$$

where Γ is the gas constant.

Also assuming local thermodynamic equilibrium and taking Rosseland's diffusion approximation [Zeldovich Raizors (6)]

$$F = - \frac{C\mu}{3} \frac{\partial}{\partial r} (\sigma T^4) , \quad (2.6)$$

where $\sigma C/4$ is the Stefan - Boltzmann constant, C the velocity of light and μ the mean free path of radiation is a function of density and absolute temperature T .

Following Wang [7]

$$\mu = \mu_0 \rho^\alpha T^\beta , \quad (2.7)$$

where μ_0 , α , β , being constant. In the self similar model the total energy of the wave is dependent of time as

$$E = B t^q , \quad (q < 0) , \quad (2.8)$$

where B and q are constant

The flow variables immediately ahead of shock denoted by suffix (1) are

$$U_1 = 0 , \quad p_1 = A R^{-W} , \quad (0 < W < 2) , \quad (2.9)$$

where A is a constant and R denotes the radius of the shock surface ahead the shock, the magnetic field distribution is

$$h = C R^{-\beta} , \quad 2\beta = W+1$$

and pressure distribution ahead the shock .

$$P_1 = \frac{AGMR^{-(1+w)}}{(W+1)} + \frac{(1-\beta)}{\beta} C^2 R^{-2\beta}, \quad (2.11)$$

where C , W and β are constant . The Rankine Hugoniot shock conditions headed by an isothermal shock is

$$\rho_2 (V - u_2) = \rho_1 V = m_s, \quad (2.12)$$

$$P_2 + \frac{h_2^2}{2} - P_1 - \frac{h_1^2}{2} = m_s u_2, \quad (2.13)$$

$$E_2 + \frac{P_2}{\rho_2} + \frac{h_2^2}{2} + \frac{1}{2} (V - u_2)^2 - \frac{F}{m_s} = E_1 + \frac{P_1}{\rho_1} + \frac{1}{2} V^2 + \frac{h_1^2}{\rho_1} \quad (2.14)$$

$$h_2 (V - u_2) = h_1 V, \quad (2.15)$$

$$T_1 = T_2, \quad (2.16)$$

where suffix 2 , denotes the flow variable just behind the shock and 1 denotes flow variable just ahead the shock . m_s denotes the mass perunit area across the shock and V be the shock velocity and

given by

$$V = \frac{dR}{dt} \quad (2.17)$$

3. TRANSFORMATION OF EQUATIONS OF MOTION

In order to reduce the equation of flow to ordinary differential equation we now introduce the following transformations .

Following Sedov [7]

$$\eta = (\alpha M G)^{-1/3} r t^{-\sigma} \quad (3.1)$$

$$\text{where } \sigma = \frac{2}{3} = \frac{2+q}{5-W} \quad ,$$

$$q = \frac{2}{3} (2 - W) \quad (3.2)$$

and the limit of q and w are

$$0 < q < 4/3 \text{ and } 0 < W < 2 \quad (3.3)$$

We see the solution of equation (2.1) - (2.4) in the form

$$u = \frac{r}{t} V(\eta) \quad , \quad p = \frac{A M G t^2}{r^{W+3}} R(\eta) \quad ,$$

$$P = \frac{AMB}{W+1} \quad P(n) \quad , \quad h = \frac{(AMB)^{\frac{1}{2}}}{W+1} \quad h(n) \quad , \quad (3.4)$$

$$F = \frac{AMB}{W+1} \quad F(n) \quad ,$$

using equation (3.1) in the equation (2.6) with the help of equation (2.5) we obtain

$$\alpha = \frac{W}{W+1} \quad \text{and} \quad \beta = \frac{-(5W+7)}{2(W+1)} \quad .$$

The equation (2.1) - (2.4) and the equation (2.5) are then transformed with the help of the relations (3.1) and (3.3) to following form

$$V(n) =$$

$$\frac{1}{N} \frac{F(n) R^{\beta-\alpha+4}}{\beta+3} - (V-\sigma) - (V-\sigma) [2np + (W+1)(p+H)] - H R - \frac{R}{\alpha n^3} + (W+1)Vp - 2p - \frac{(1-W)}{2} V H^2$$

$$[np - nR (V - \sigma)^2 + n^2 H^2]$$

$$\text{where } N = \frac{4}{3} \frac{C_{100\sigma}}{\Gamma} (AMB)^{\alpha-1} \quad , \quad (3.6)$$

is a dimension less parameter

$$\frac{R'}{R} = \frac{1}{(V-\sigma)} \left[\frac{(W+1)}{\Pi} V'(\Pi) - V'(\Pi) - \frac{2}{\Pi} \right] \quad (3.7)$$

$$P'(\Pi) = \frac{(W+1)}{\Pi} [P + H] - \frac{H^2 R}{\Pi^4} - \frac{R}{\Pi} - \frac{VR(V-1)}{\Pi} - HH' \quad (3.8)$$

$$F'(\Pi) = \frac{1}{(\tau-1)} \left[\frac{\Pi R P'}{R} - P' \right] (V-\sigma) + \frac{2\tau P}{(\tau-1)\Pi} - \frac{P V}{\Pi(\tau-1)} [W(\tau-1) + 3\tau - 1] \\ - \frac{(1-W)}{\Pi} F'(\Pi) \quad (3.9)$$

4. RESULT AND DISCUSSIONS .

The transformed jump condition at the shock front is given by

$$V(1) = \frac{2}{(4+W)} \left[1 - \frac{1}{\tau M^2} - \frac{1}{\tau M^2 A} \right] \quad (4.1)$$

$$R(1) = \frac{\tau M^2 M^2}{A} \quad (4.2)$$

$$P(1) = \frac{4}{(4+W)} \frac{\frac{M^2}{A}}{\frac{M^2 + M^2}{A}} \quad (4.3)$$

$$F(1) = \frac{-4}{(4+W)} \left[\frac{\frac{M^2}{A} + \frac{M^2}{A}}{\tau M + M^4} - 1 \right] \quad (4.4)$$

$$H(1) = \frac{4}{(4+W)} \left[\frac{\frac{3}{\tau M}}{\frac{2}{\tau M} + \frac{2}{\tau M} + \frac{2}{\tau M}} + \frac{\frac{2\tau M}{A}}{\frac{2}{\tau M} + \frac{2}{\tau M} + \frac{2}{\tau M}} - 1 \right] \quad (4.5)$$

For exhibiting the numerical solution it is convenient to write the field variables in non dimensional form

$$\frac{u}{u_2} = \pi \frac{V(\pi)}{V(1)} \quad (4.6)$$

$$\frac{\rho}{\rho_2} = \frac{1}{\pi} \frac{R(\pi)}{w+3} \frac{R(1)}{R(1)} \quad (4.7)$$

$$\frac{P}{P_2} = \frac{1}{n^{w+1}} \frac{P(n)}{P(1)}, \quad (4.8)$$

$$\frac{h}{h_2} = \frac{1}{n^{(w+1)/2}} \frac{H(n)}{H(1)}, \quad (4.9)$$

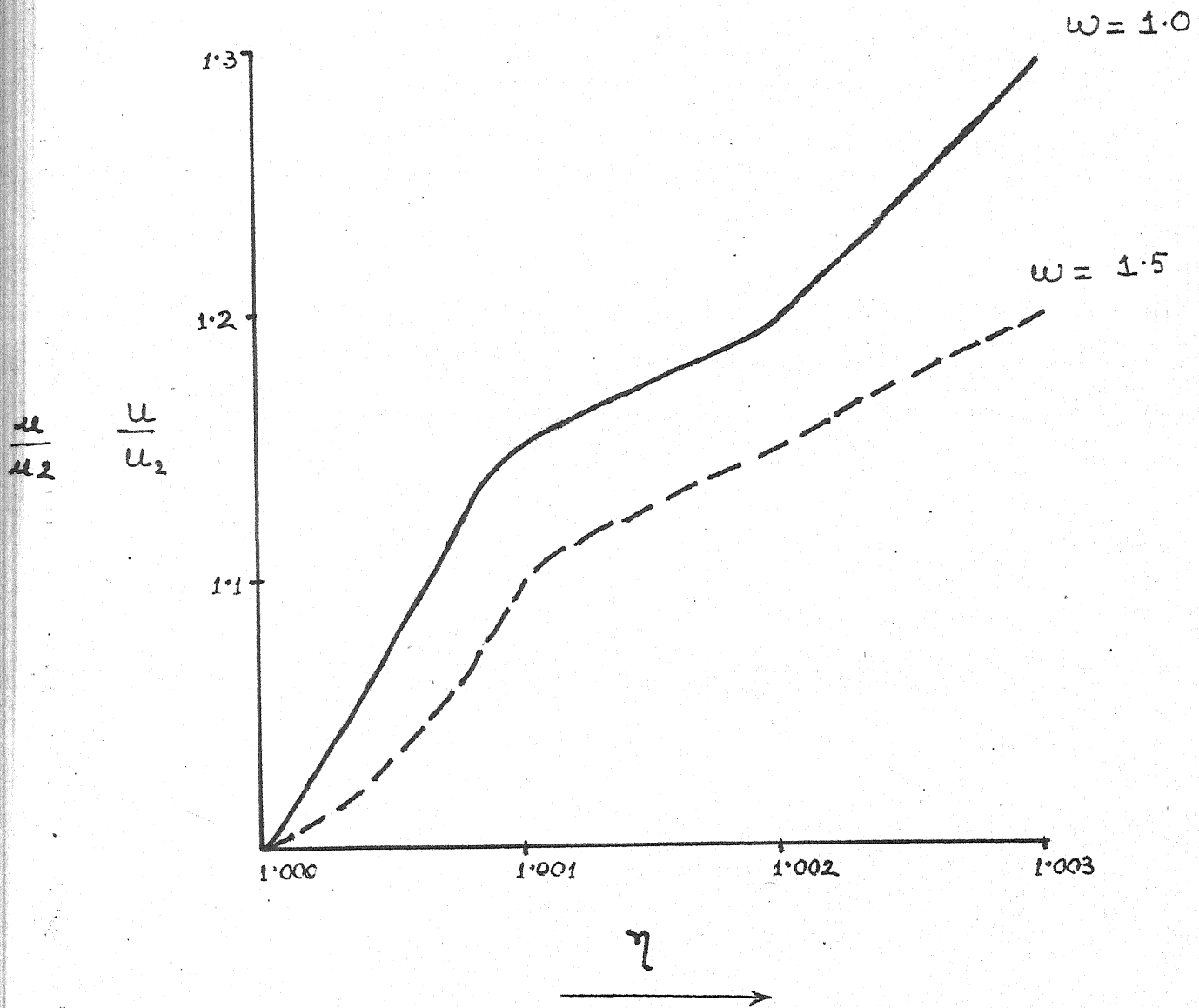
$$\frac{f}{f_2} = \frac{1}{n^w} \frac{F(n)}{F(1)}. \quad (5.0)$$

The numerical integration is carried out on DEC-system 1090 computer installed at I.I.T. Kanpur by well known R.K.G.S programme for the values of $w=1, 1.5$.

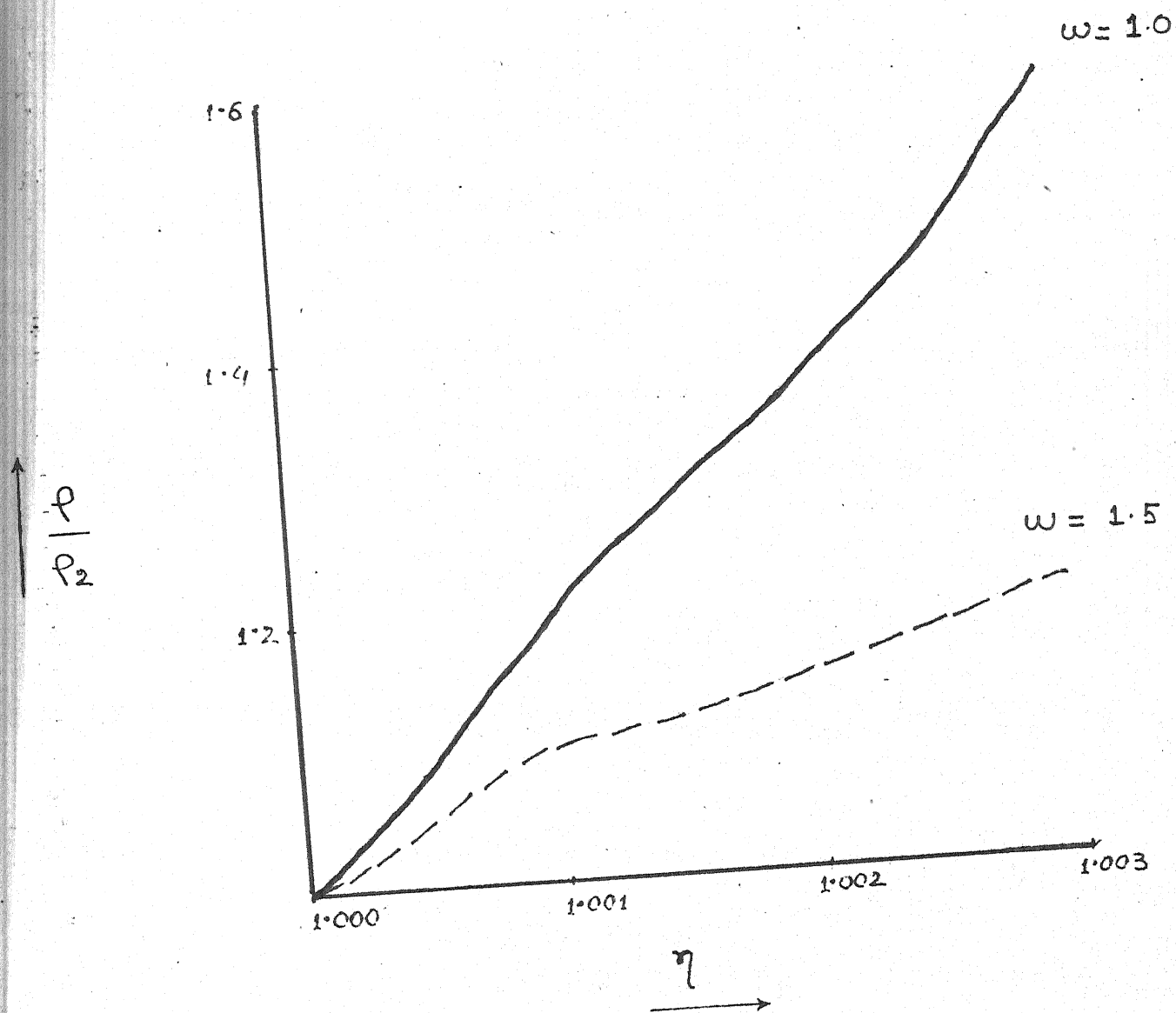
The other parameters are

$$M = 15, M_A = 25, \alpha = 1/3, \beta = \frac{-(7+5w)}{2(1+w)}, N=10.$$

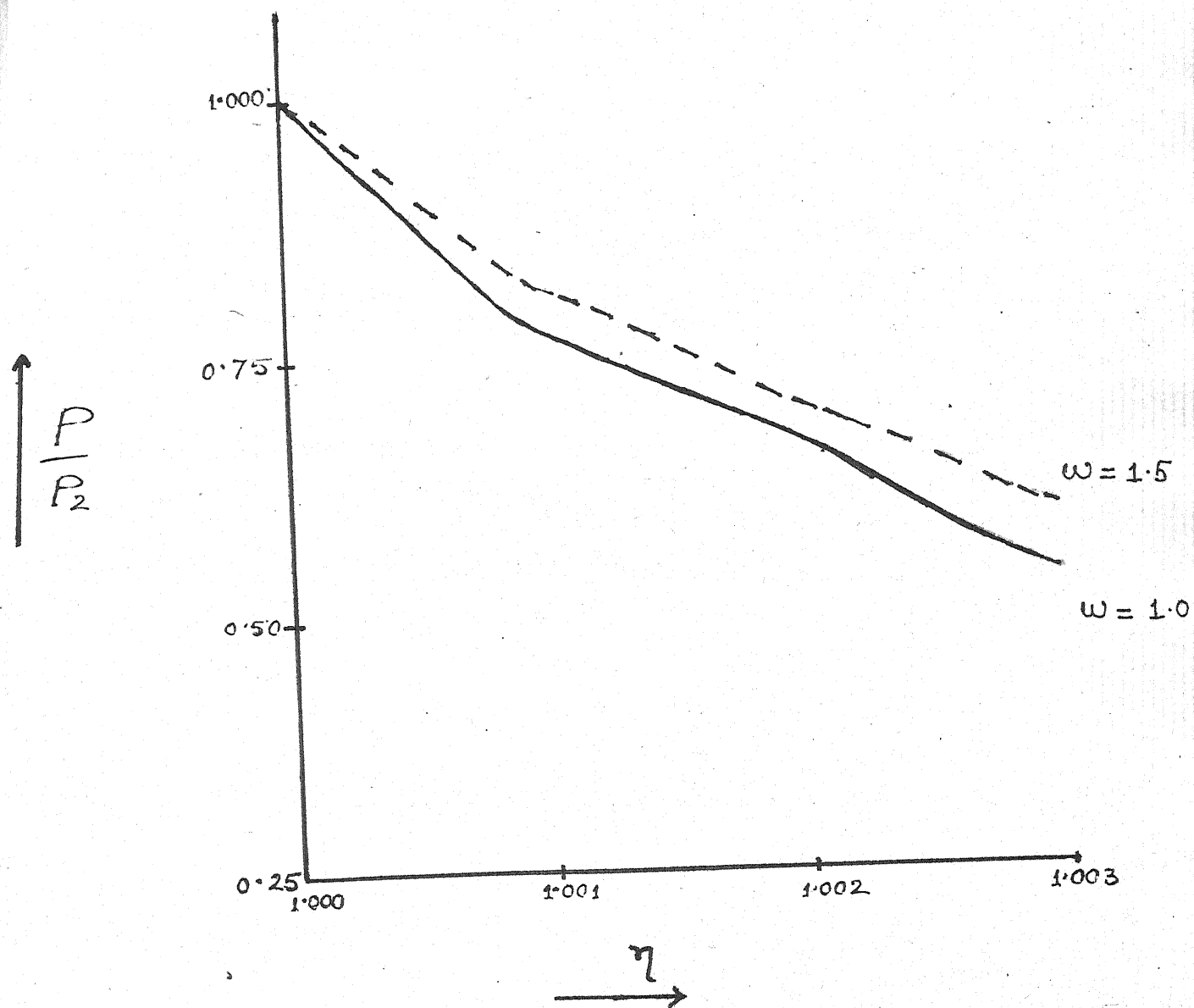
The nature of flow and field variables for adiabatic case are illustrated through graphs, it is clear from the graphs that velocity, density and pressure are minimum at shock front but increases rapidly towards the center of explosion in adiabatic case. Whereas distribution of magnetic field and radiation heat flux is maximum at shock front but decreases towards the centre of explosion.



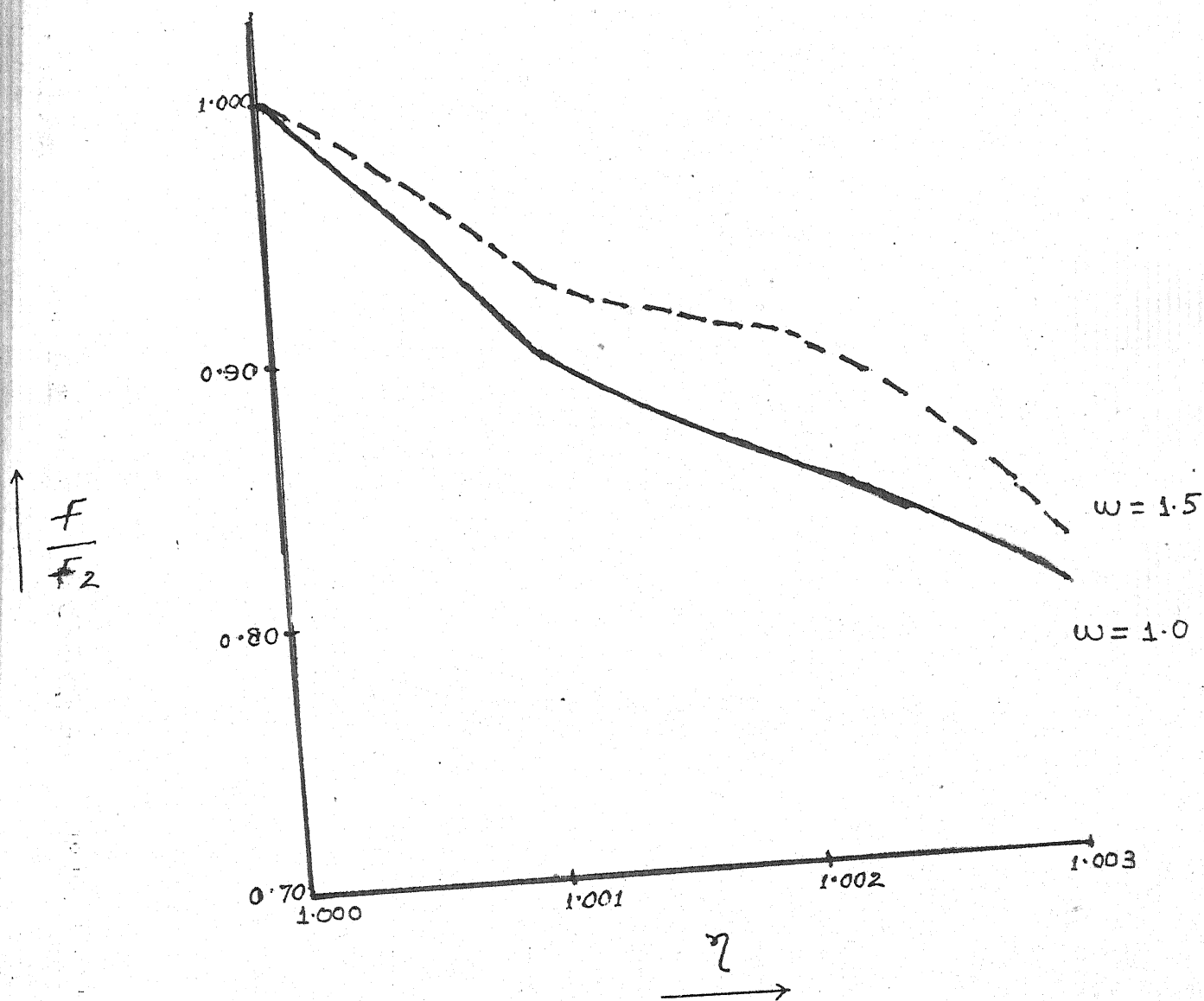
VELOCITY DISTRIBUTION



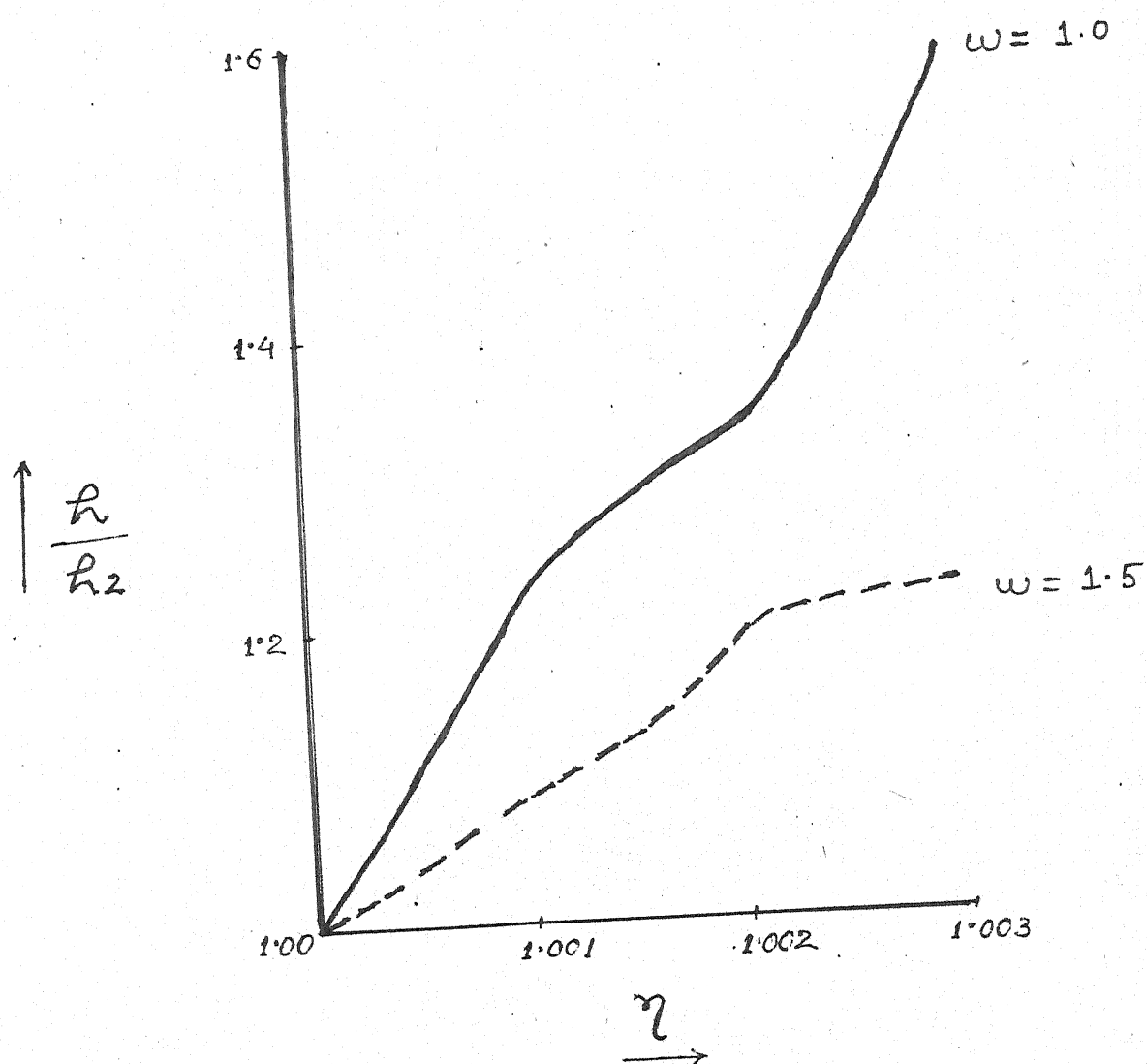
DENSITY DISTRIBUTION



PRESSURE DISTRIBUTION



RADIATION DISTRIBUTION



MAGNETIC FIELD DISTRIBUTION

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CHAPTER - V

ANALYSIS OF SELF SIMILAR MOTION IN THE THEORY OF STELLAR
EXPLOSION

(1) INTRODUCTION

Carrus et al [1] and Sedov [2] were first to discuss the model of stellar explosion in which a star is considered to be a perfect self gravitating gas. The distribution of gas at any moment of time spherically symmetric. In the present chapter a analytical solution of the classical model of stellar explosion has been investigated. A number of new solutions has been obtained in which radial oscillation of gas occur after the shock wave passes. Taking Newtonian gravitation into account a thorough analytical study of self similar motion of a gas dynamics under the effect of magnetic field is developed in the theory of stellar explosion which was earlier applied by Novikov[3] and Bogoyavlensky[4]. It is supposed that originally the star is in equilibrium state the gas density ρ , the pressure P , the mass M of the gas within sphere of radius r , the radial gas velocity u , the magnetic field h have the form

$$p_1 = A r_1^{-w}, u_1 = 0, M_1 = \frac{4\pi A r_1^{3-w}}{3-w},$$

$$h_1 = C r_1^{-k}, 2k = w + 1,$$

(1.1)

$$P = \frac{2\pi A G}{1} \frac{r^{2(1-w)}}{(3-w)(w-1)} + \frac{C(1-k)}{2K} \frac{r^{-2K}}{r}$$

where A, w and G are constant. As a result of energy libration at the centre of symmetry $r=0$: a shock wave travels out from the centre. The motion of gas behind the shock front self similar and adiabatic

$$\frac{d}{dt} \left(\frac{P}{\rho} \right) = 0 \quad , \tau > 1 \quad (1.2)$$

(2) EQUATION OF MOTION AND BOUNDARY CONDITION

The fundamental differential equation signifying the conservation laws of spherically symmetric motion in a self gravitating gas, where the magnetic field is significant are Summer[5]

$$\frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial r} + \frac{\rho}{r} \frac{\partial}{\partial r} (ur^2) = 0 \quad (2.1)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} + \frac{1}{\rho} \frac{\partial p}{\partial r} + \frac{h}{\rho} \frac{\partial h}{\partial r} + \frac{1}{\rho} \frac{h^2}{r} + \frac{GM}{r^2} = 0 \quad (2.2)$$

$$\frac{\partial P}{\partial t} + u \frac{\partial P}{\partial r} - \frac{\tau P}{\rho} \left(\frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial r} \right) = 0 \quad (2.3)$$

$$\frac{\partial h}{\partial t} + u \frac{\partial h}{\partial r} + h \frac{\partial u}{\partial r} + h \frac{u}{r} = 0. \quad (2.4)$$

$$\frac{\partial M}{\partial r} = 4\pi r^2. \quad (2.5)$$

where r, t, u, ρ, P, M are radial distance from centre . time . velocity . density . pressure and mass contained in a sphere of radius r

The disturbance is headed by an isothermal shock with condition

$$\rho_2 (v-u)^2 = \rho_1 v^2 = m. \quad (2.6)$$

$$\rho_2 + \frac{h_2^2}{2} - \rho_1 - \frac{h_1^2}{2} = m u. \quad (2.7)$$

$$h_2 (v-u)^2 = h_1 v^2. \quad (2.8)$$

$$E + \frac{p_2}{2} + \frac{1}{2} (v-u)^2 + \frac{h_2^2}{2} = E + \frac{p_1}{2} + \frac{1}{2} v^2 + \frac{h_1^2}{2}. \quad (2.9)$$

$$T = T_1 = T_2, \quad (2.10)$$

$$M = M_1 = M_2, \quad (2.11)$$

where suffix 1 and 2 denotes the flow variables just ahead and just behind the shock front respectively denotes the mass flux per unit area across shock and V denote velocity of shock, is given by

$$V = \frac{dr}{dt} \quad (2.12)$$

According to Sedov [5], the total energy of gas between spheres of radii r_1 and r_2 in equilibrium is

$$E = 8\pi G A \frac{r_2^{5-2w} - r_1^{5-2w}}{(1-\tau)(w-1)(3-w)(5-2w)}, \quad (2.13)$$

$$E = \frac{32\pi(4-3\tau)}{3(\tau-1)} \log \frac{r_2}{r_1}$$

If $w < 5/2$, the total energy E enclosed within the sphere of radii r is finite if $w \geq 5/2$ it is infinite but $E < 0$ if $\tau > \tau_0$ and $E \geq 0$ if $\tau \leq \tau_0$ where $\tau_0 = 2w - 1 / 2(w-1)$. The

solutions of the problem of stellar explosions for $w \geq 5/2$ in the class of gas motion considered can only be applied to certain astrophysical solutions because of divergence of E at the lower limit. These solutions are regarded as intermediate asymptotic solutions valid outside a small neighbourhood of $r = 0$, solutions with $\tau \leq \tau_0$ ($E \geq 0$) describe the break down of unstable stellar equilibrium. The law of energy liberation in a self similar solutions has the form (Bogoyaslenky [4])

$$E = \alpha G \frac{(5-w)/w}{A} \frac{5/w}{t} \frac{2 [5-2w] / w}{t} \quad (2.14)$$

Evidently E is independent of the time for $w = 5/2$ or $\alpha=0$. The constant α is calculated from the solution it self and in some case turn out to be infinite. The corresponding solutions then provided asymptotic form for a very intense explosion. The following new results may directly be deduced by

(1) For $\tau < 4/3$, $w = 5/2$ and also for $\tau < 2(w-1)/3$ there exist no solution with a vacuum forming within the gas

For $\tau < 4/3$, $w = 5/2$, $M=1$, damped Oscillation of the gas occur after the shock wave passes which are connected with the limit of dynamic system

(2) For $\tau < 4/3$, $w = 5/2$ all solutions have a spherically vacuum of increasing radii which forms about the centre. the gas monotonically spreading out from it.

(3) For $\tau < 1/4$, $w = 5/2$, $M=1$, the gas returns to equilibrium after the shock wave passes but in case when

$$\tau < \tau_1 = \frac{4[3 + (2w-5)^2]^{-1}}{8(w-1)}$$

repeated damped oscillation taken place.

(3) SIMILARITY SOLUTIONS

The similarity variables which reduce the equation governing the flow to ordinary differential equation is taken as

$$P = \frac{1}{2} \frac{R(n)}{Gt} .$$

$$P = \frac{r^2}{4(Gt)} P(n) .$$

$$M = \frac{r^3}{2(Gt)} M(n) . \quad (3.1)$$

$$V = \frac{r}{t} V(n) .$$

$$\text{where } n = r (AGt)^{-1/W} .$$

By using relation (3.1) the differential equation are transformed as

$$-V + V + \frac{2}{n} \frac{\partial V}{\partial n} \left[V - \frac{2}{W} \right] + \frac{2p}{r} + \frac{n}{R} \frac{\partial P}{\partial n} + \frac{2N}{R} + \frac{N}{R} \frac{\partial N}{\partial n} + M = 0 . \quad (3.2)$$

$$-\left[\frac{2n}{W} \frac{\partial P}{\partial n} + 4p \right] V(n) \left[2p + n \frac{\partial P}{\partial n} \right] - \frac{TP}{R} \left[-2 \left\{ \frac{n}{W} \frac{\partial R}{\partial n} + R \right\} + n V \frac{\partial R}{\partial n} \right] = 0 . \quad (3.3)$$

$$[-2N - \frac{2\pi}{w} \frac{\partial N}{\partial \pi}] + \pi N \frac{\partial N}{\partial \pi} + 3VN + \pi N \frac{V}{\pi} = 0, \quad (3.4)$$

$$-2[\frac{\pi}{w} \frac{\partial V}{\partial \pi} + R] + \pi V \frac{\partial R}{\partial \pi} + [3VR + R \frac{\partial V}{\partial \pi}] = 0, \quad (3.5)$$

and appropriate transformed jump conditions are

$$V(1) = \frac{2}{3} \Omega,$$

$$R(1) = \frac{V}{1-\Omega},$$

$$P(1) = \frac{2V}{9} \left[\Omega + \frac{1}{\tau M^2} - \frac{\Omega(2-\Omega)}{2(1-\Omega)} \frac{M_A^{-2}}{M^2} \right],$$

$$N(1) = \frac{2}{3} (V) \left[\frac{1}{1-\Omega} \right] \frac{M_A^{-1}}{M}, \quad (3.6)$$

where

$$\Omega = \left(1 - \frac{2}{\tau M^2} - \frac{M_A^{-2}}{4} \right) - \left[\left(\frac{1}{2\tau M^2} + \frac{M_A^{-2}}{4} \right)^2 + \frac{M_A^{-2}}{2} \right],$$

and

$$V = \frac{9}{2} \tau M^2 \left[2(1+W) - \frac{\tau M^2}{M_A^2} (1-W) \right]^{-1},$$

To Investigate numerical flow solution we write flow variable in a non dimension form

$$\frac{u}{u_2} = \eta \frac{V(\eta)}{V(1)},$$

$$\frac{\rho}{\rho_2} = \frac{R(\eta)}{R(1)}, \quad (3.7)$$

$$\frac{P}{P_2} = \eta \frac{P(\eta)}{P(1)}$$

$$\frac{h}{h_2} = \eta \frac{N(\eta)}{N(1)},$$

$$\frac{M}{M_2} = \eta \frac{M(\eta)}{M(1)}.$$

DISCUSSION

Above relations show the distribution of velocity, density, pressure, magnetic field and mass distribution in the stellar model, when magnetic field is applied. A numerical approximation may also be obtained which may illustrate the behaviour of flow and field variables exactly behind the surface of discontinuity.

CHAPTER - VI

AN EXACT SOLUTION OF NORMAL SHOCK WAVE OF VARIABLE STRENGTH

ADVANCING INTO A REGION OF VARIABLE DENSITY

INTRODUCTION

The propagation of normal shock wave in a half space, due to point explosion or a line explosion has been discussed by many workers to some levels of approximation. This approximation seems to have been originated by S.W. Yuan and various Co-workers ([1],[4]) who have further approximated the solution of the resulting equations by seeking a variety of quasi-similar solutions. Kynch [5], Taylor [6] assumed the undisturbed density to vary according to some inverse power of the distance from the center of explosion and neglected the counter pressure. This chapter aims to find an analytical solution, representing a progressive wave applied to the problem of shock advancing into region where the pressure is constant but the density varies according as power law.

(2) FUNDAMENTAL EQUATIONS

In Eulerian co-ordinates, the equations of motions are given as [7]

$$\frac{\partial p}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\rho u^2}{x} = 0, \quad (2.1)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + \frac{1}{\rho} \frac{\partial p}{\partial x} = 0, \quad (2.2)$$

$$\frac{\partial s}{\partial t} + u \frac{\partial s}{\partial x} = 0, \quad (2.3)$$

where $n=0,1,2$ for one dimensional plane, cylindrical and spherically symmetric flow : x the radial distance from the line of explosion ; ρ density ; P pressure ; u radial velocity and s is the entropy

The shock pressure is an electrically and thermally , we also have

$$P = C_p e^{\tau (\tau k s)} \quad (2.4)$$

$$\text{where } k = \frac{1}{C_p} \text{ and a sound speed is } a = \frac{\tau P}{\rho}.$$

ie., $a^2 = \tau C_p e^{\tau k s}$ with the entropy s and time t as independent variables, the equations (2.1) to (2.3) can be written as

$$\frac{\partial \rho}{\partial t} + \frac{\partial u / \partial s}{\partial x / \partial s} + \rho \frac{nu}{x} = 0, \quad (2.5)$$

$$\frac{\partial u}{\partial t} + \frac{1}{\rho} \frac{\partial p / \partial s}{\partial x / \partial s} = 0, \quad (2.6)$$

$$\frac{\partial x}{\partial t} - u = 0, \quad (2.7)$$

$$\text{and also } \frac{\partial F}{\partial \xi} = a^2 (p\xi + k\rho), \quad (2.8)$$

Now, we try to find an exact and special solution of the equations of motion,

(2) SOLUTION TO THE PROBLEM

We choose a variable

$$\eta = t \exp\left(\frac{-k\xi/\alpha}{\alpha}\right), \quad (3.1)$$

where α is a constant to be determined. To obtain the solution, we can take the variables in the following form

$$x = t^b X(\eta), u = t^{b-1} U(\eta), \rho = t^c \Omega(\eta), \quad (3.2)$$

$$F = t^{2b+c-2} P(\eta).$$

Differentiating (3.2) with respect to η , equations (2.5), (2.8) can be reduced to ordinary differential equations for X, U, Ω , and P as

$$X' (c \Omega X + \eta \Omega X + \eta \Omega U) + U \Omega X' = 0, \quad (3.3)$$

$$P' + \Omega X' \{ (b-1) U + \eta U' \} = 0, \quad (3.4)$$

$$U = b x + \pi x' , \quad (3.5)$$

$$\frac{\pi P'}{P} = \tau \left(\pi \frac{\Omega'}{\Omega} - \alpha \right) , \quad (3.6)$$

where prime denotes differentiation .

We define the quantities Y and Z , such that

$$Y = \left(1 - \frac{bx}{U} \right) , \quad (3.7)$$

$$Z = \frac{A^2 Y^2}{U^2} , \quad (3.8)$$

$$\text{where } A^2 = \frac{\tau P}{\Omega}$$

using above new variables equation (3.1) & (3.4) can be written as

$$\pi Z \left(\frac{P'}{P} \right) + \tau Y \left\{ b - 1 + \pi \frac{U'}{U} \right\} = 0 . \quad (3.9)$$

And as a consequence of (3.5) , equation (3.7) , becomes

$$\pi \frac{x'}{U} = \frac{1}{Y} , \quad (3.10)$$

Then by using variable (3.7)& (3.8), equation (3.8) to (3.6) and (3.9)& (3.10) reduce to following form

$$\pi \frac{x'}{x} = \frac{b}{Y-1}, \quad (3.11)$$

$$\pi \frac{u'}{u} = \frac{1}{Z-1} \left\{ Y \frac{(b-1) Z (C + \alpha)}{Y} - \frac{nbz}{Y-1} \right\}, \quad (3.12)$$

$$\pi \frac{\Omega'}{\Omega} = \frac{1}{Z-1} \left\{ \alpha Z - (b-1) Y + C + \frac{nbY}{Y-1} \right\} \quad (3.13)$$

$$\pi \frac{P'}{P} = \frac{\tau}{Z-1} \left\{ C + \alpha - (b-1) Y + \frac{nbY}{Y-1} \right\}, \quad (3.14)$$

$$\pi \frac{Y'}{Y} = b - (Y-1) \pi \frac{u'}{u}, \quad (3.15)$$

$$\pi \frac{Z'}{Z} = \pi \frac{P'}{P} + 2\pi \frac{Y'}{Y} - \pi \frac{\Omega'}{\Omega} - 2\pi \frac{u'}{u}. \quad (3.16)$$

The relation (3.12) to (3.16) finally give required exact solution of the differential equation as

$$\frac{dY}{dZ} = \frac{1}{Z} \frac{Y + (c+\alpha)Z + Y^2 (b-1) - YZ (b+c+\alpha+nb)}{H}, \quad (3.17)$$

$$\text{where } H = Y(b-1)(\tau-1) - Z(2C+2b+\alpha) + 2b+C - \tau(C+\alpha) + \frac{nbY}{Y-1} + (1-\tau-2Z)$$

which although not very simple but may determine the solution. In order to find the quantities $X, U, \Omega, \& P$, we have to solve (3.17) by quadrature for $Y \& Z$ from (3.17), we derive

$$\begin{aligned} \frac{1}{\Omega} \frac{d\Omega}{dz} &= \frac{(z-1)Z}{(\tau-1)+\tau\alpha-2b} - [(\tau+1)(b-1)Y] + (2b+2C+\alpha)Z \\ &+ \frac{nbY}{Y-1} \{(\tau-1)+2Z\}. \end{aligned} \quad (3.18)$$

The shock problem suggests that $c \& \alpha$ is such that $c+\alpha=0$. This leads to a simplification of (3.17). The value $b=1$ corresponds to the case of homentropic flow.

4. STRONG SHOCK CONDITIONS

If the shock is moving with a region of gas which is at rest under uniform pressure p , but a un-uniform temperature & density. Suppose that density distribution obeys the power law

$\rho_1(x) = \sigma x^m$ where $\sigma \& m$ are constants and the suffix 1 denotes the shock condition ahead the shock. The position of shock at the

time 't will be assumed to be given by $x = x_2 = \mu t^b$ where μ being shock constant. The shock speed is $v = dx/dt = b\mu t^{b-1}$ where suffix 2 denotes the quantities just behind the shock

so if, $\lambda = \frac{\tau-1}{\tau+1}$, then

$$\frac{\rho_2}{\rho_1} = \frac{p_2 + \lambda p_1}{p_1 + \lambda p_2} \quad (4.1)$$

$$p_2 + \lambda p_1 = (1-\lambda) p_1 v^2 \quad (4.2)$$

$$u_2 = (1-\lambda) \left(v - \frac{a}{v} \right) \quad (4.3)$$

Let $\eta = \eta$ represent the shock position, then eq (3.2) gives

$$P_2 = t^{2b+c+2} P(\eta) \quad (4.4)$$

$$p_2 = t^c \Omega(\eta) \quad (4.5)$$

$$u_2 = t^{b-1} U(\eta) \quad (4.6)$$

we may also write

$$\rho_1 = \sigma \mu t^{\frac{m}{2}}, \quad (4.7)$$

$$\text{and } a = \frac{\tau \rho_1}{\rho_1} = \left(\frac{\tau \rho_1}{\sigma \mu^m} \right) t^{-\frac{bm}{2}}, \quad (4.8)$$

Putting these expressions in (4.1) to (4.3), powers of t can be eliminated if the constants b & c are such that

$$2b+c-2=0, m b - c = 0, \quad (4.9)$$

$$\text{which give } b = \frac{2}{m+2}, c = \frac{2m}{m+2}. \quad (4.10)$$

The value $b=1$ corresponds to $m=0$ which shows that the flow is uniform & homentropic. The approximated conditions for a strong shock are obtained by neglecting p_1 , so that (4.2) to (4.4) become

$$p_2 = \lambda p_1^{-2}, \quad (4.11)$$

$$P_2 = (1-\lambda) p_1^2 v^2, \quad (4.12)$$

$$u = (1-\lambda) v^2, \quad (4.13)$$

There is a condition to be satisfied by λ to be a constant
from (2.4) to (3.1) we get

$$n = t \left(\frac{P}{c p^{\frac{1}{2}}} \right)^{-1/\tau\alpha} = c^{\frac{1}{1\alpha}} t^{(\tau\alpha + \tau c - 2b - c - 2)/\tau\alpha} \left(P(n) \right)^{-1/\tau\alpha} \left(\Omega(n) \right)^{1/\alpha}$$

by eliminating power of t we get $C + \alpha = 0$

which gives
$$\frac{n^{\tau\alpha}}{2} P(n) = C \left(\frac{\Omega(n)}{2} \right)^{\alpha}$$

we also have

$$U(n) = (1 - \frac{2}{\tau+1}) b \mu = \frac{2b\mu}{\tau+1}, \quad (4.14)$$

$$X(n) = \mu,$$

$$\frac{bX(n)}{U(n)} = \frac{1}{2} (\tau+1),$$

$$\Omega(n) = \lambda^{-2} \sigma^m U = \frac{\tau+1}{\tau-1} \sigma U, \quad (4.15)$$

$$P(n) = \frac{2^{m+2} \sigma b \mu}{(\tau+1)^2}. \quad (4.16)$$

Hence
$$A(n) = \frac{2^{2\tau(\tau-1)}}{(\tau+1)^2} \frac{2}{b} \mu^2. \quad (4.17)$$

Finally the equation to determine \bar{n}_2 become

$$\bar{n}_2 = \frac{\tau \alpha}{2} \frac{1}{c(\tau+1)} \frac{\tau+1}{\sigma} \frac{\tau-1}{b} \frac{-2}{\mu} \frac{m(\tau-1) - 2}{(\tau-1)} \frac{-\tau}{\tau-1} \quad (4.18)$$

So equations (4.14) to (4.18) constitute the boundary conditions for strong shock problem

Hence equation (3.18) with $\alpha+c=0$ and special values of the constant etc becomes

$$\frac{dY}{dZ} = \frac{Y(m+2) - mY - 2Z(n+1)}{ZmY(-\tau-1) + 2(m+2)(1-Z) + (2nY)(1-\tau-2Z)/(\tau-1)} \quad (4.19)$$

Boundary values for Y and Z are easily obtained from (4.14) & (3.11) and leads to simple value given as

$$Y = Y(\bar{n}) = -\frac{2}{Y-1}, \quad Z = Z(\bar{n}) = \frac{2Y}{\tau-1} \quad (4.20)$$

Then the slope dY/dZ at this point is given by

$$\left(\frac{dY}{dZ} \right)_{Y=Z=1} = \frac{(m-2)(\tau+1) - 4nY}{4\tau(n+1)(\tau+1)} \quad (4.21)$$

The values of Y, & Z, define unique integral curves.

5. CONCLUSION

Although a general description for any value of m is possible, we examine only for $m=1$ and 2 and making a comparative study of slopes and the different flows considered for $m=1$, $\tau = 1.4$, we have

$$\left(\frac{dY}{dZ} \right)_{-5,7} = -0.1786 \quad (5.10)$$

Similarly for $m=2$, $\tau=1.4$, we have

$$\left(\frac{dY}{dZ} \right)_{-5,7} = 0, \text{ when } n=0 \quad (5.20)$$

$$\left(\frac{dY}{dZ} \right)_{-5,7} = -0.2083, \text{ when } n=1 \quad (5.30)$$

$$\left(\frac{dY}{dZ} \right)_{-5,7} = -0.2087, \text{ when } n=2 \quad (5.40)$$

By observing the slopes in above cases at point (Y_1, Z_1) it is

seen that for $m=1$, angle of slope has a decreasing tendency as the flow is takes from one dimensional to spherical and spherical to cylindrical where as for $m=2$ the tangent to integral curves is parallel to Z axis for one dimensional flow but flow turns through small angle and remain almost stationry in the case of spherical and cylindrical flows.

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CHAPTER VII

ANALYTICAL SOLUTIONS OF CYLINDRICAL SHOCK WAVES IN A ROTATING GAS

WITH AZIMUTHAL MAGNETIC FIELD

(1) INTRODUCTION

The propagation of hydromagnetic shock through a rotating gas being close to the actual situation of thunder. Kumar and Prakash [1,2,3] recently using C.C.W. [4,5,6] method have investigated the propagation of weak and strong diverging cylindrical hydromagnetic gas taking density distribution variable but axial component of magnetic field of constant strength.

In this chapter, using the C.C.W. method we have considered the problems of the propagation of a converging and diverging cylindrical shock wave through a rotating gas under the influence of a magnetic field of constant axial and azimuthal components, simultaneously for both weak and strong waves. We have assumed initial distribution is constant.

The analytical expression for shock velocity and shock strength have been obtained for weak shock under the two conditions, namely when the magnetic field is weak and when the magnetic field is strong. For strong shock also we have considered two cases, i.e. when the magnetic field is strong and when ρ_0/ρ_1 is approximately equal to $\tau+1/\tau-1$, which is purely a non magnetic case.

(2) BASIC EQUATIONS BOUNDARY CONDITION AND AN ANALYTIC EXPRESSION

FOR SHOCK VELOCITY

The equation governing the cylindrically symmetrical flow of rotating gas under the influence of transverse magnetic field are written as

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} + \frac{1}{\rho} \frac{\partial p}{\partial r} - \frac{v^2}{r} + \frac{\mu}{2\rho} \frac{\partial}{\partial r} \left(H_\theta^2 + H_z^2 \right) + \frac{\mu H_\theta^2}{r} = 0$$

$$\left(\frac{\partial}{\partial t} + u \frac{\partial}{\partial r} \right) (Vr) = 0,$$

$$\frac{\partial p}{\partial t} + u \frac{\partial p}{\partial r} + p \left(\frac{\partial u}{\partial r} + \frac{u}{r} \right) = 0, \quad (1)$$

$$\frac{\partial p}{\partial t} + u \frac{\partial p}{\partial r} - a^2 \left(\frac{\partial p}{\partial t} + u \frac{\partial p}{\partial r} \right) = 0,$$

$$\frac{\partial H_\theta}{\partial t} + u \frac{\partial H_\theta}{\partial r} + H_\theta \frac{\partial u}{\partial r} = 0,$$

$$\frac{\partial H_z}{\partial t} + \frac{\partial H_z}{\partial r} + H_z \left(\frac{\partial u}{\partial r} + \frac{u}{r} \right) = 0,$$

where u , P and ρ are the velocity, pressure and density behind the shock front respectively while H_θ and H_z are azimuthal and axial components of magnetic field H .

The magnetogasdynamic shock conditions can be written in terms of a single parameter.

$$N = \frac{\rho_1}{\rho_0} \quad \text{as}$$

$$\rho_1 = \rho_0 N, \quad H_1 = H_0 N, \quad u_1 = \frac{N-1}{N} U,$$

$$U^2 = \frac{2N}{(\tau+1) - (\tau-1)N} \left[a^2 + \frac{b_0^2}{2} + \{ (2-\tau)N + \tau \} \right], \quad (2)$$

$$P_1 = P_0 + \frac{2\rho_0(N-1)}{(\tau+1) - (\tau-1)N} \left[a^2 + \frac{\tau-1}{4} b^2 (N-1) \right],$$

where 0 and 1 denote respectively the states immediately ahead and behind the shock front; U the shock velocity, a the sound speed $(\tau P_0/\rho_0)$ and the Alfvén speed is $(\mu H^2/\rho_0)$ where

$$H_0^2 = H_{\theta 0}^2 + H_{z0}^2 \quad .$$

In the equilibrium state we have

$$\frac{1}{\rho_0} \frac{dp_0}{dr} + \frac{\mu}{\rho_0} \frac{H_{\theta}^2}{r} - \frac{V^2}{r} = 0 \quad . \quad (3)$$

Integrating the preceeding equation we get

$$P = K \log \frac{A}{r} \quad \text{and} \quad a_0 = K \left[\log \frac{A}{r} \right]^{1/2} \quad , \quad (4)$$

$$\text{where } k = \left(\mu H_{\theta 0}^2 + \rho' V^2 \right) \quad , \quad K = \left(\frac{\gamma k_1}{\rho'} \right)^{1/2} \quad \text{and}$$

$$\left[\mu H_{\theta 0}^2 + \rho' V^2 \right] \log A \text{ is constant of integration}$$

WEAK SHOCKS

For a very weak shock we take the parameter N as

$$\frac{\rho}{\rho_0} = N = 1 + \epsilon, \quad \epsilon \ll 1. \quad (5)$$

Now consider the two cases of weak and strong magnetic field

CASE - I

When the magnetic field is weak i.e. $b_0^2 \ll a_0^2$ (i.e. $\mu H_0^2 \ll \tau P_0$)

and therefore the boundary conditions (2) reduce to

$$\rho_1 = \rho_0 (1 + \epsilon), \quad u_1 = b_0 \epsilon, \quad H_1 = H_0 (1 + \epsilon)$$

$$H_1 = H_0 (1 + \epsilon), \quad P_1 = P_0 (1 + \tau \epsilon), \quad (6)$$

$$U = \left(1 + \frac{\tau+1}{4}\right) \frac{a_0}{\rho_0}$$

CASE II

When magnetic field is strong $b_0^2 \gg a_0^2$ (i.e. $\mu H_0^2 \gg \tau P_0$)

under these circumstances the boundary condition (2) reduce to

$$p_1 = p_0 (1 + \epsilon), \quad u_1 = u_0, \quad H_1 = H_0 (1 + \epsilon) \quad (7)$$

$$H_1 = H_0 (1 + \epsilon), \quad P_1 = P_0 (1 + \tau \epsilon),$$

$$U = (1 + \frac{3}{4} \epsilon) u_0.$$

STRONG SHOCK

CASE - I

When the magnetic field is strong $b_0^2 \gg a_0^2$, (i.e., $\mu H_0^2 \gg \tau P_0$)

under this condition the boundary conditions (2) becomes

$$P_1 = P_0 N, H_1 = H_0 N, U_1 = \frac{N-1}{N} U_0, \frac{P_1}{P_0} = \frac{X U_1^2}{a_0^2} + L,$$

where

(8)

$$X = \frac{\tau(\tau-1)(N-1)^3}{2N\{(2-\tau)N+\tau\}} \text{ and } L = \frac{(\tau+1)N-(\tau-1)}{(\tau+1)-(\tau-1)N},$$

CASE - II

For strong shock when $b \ll a$ (i.e. when $N \rightarrow [(\tau+1)/(\tau-1)]$ is small)

the field may be regarded as independent of magnetic field.

For converging shock the characteristic form of system of equations (2) is

$$dP + \mu \left(H_\theta \frac{dH_\theta}{d\theta} + H_z \frac{dH_z}{dz} \right) - \rho c du + \left[\frac{\rho c^2 u}{u-c} - \frac{\mu H_\theta^2 (u+c)}{u-c} + \frac{\rho c v^2}{u-c} \right] \frac{dr}{r} = 0, \quad (9)$$

where as the characteristic form for diverging shock is

$$dP + \mu \left(H_{\theta}^2 \frac{dH}{dz} + H_z^2 \frac{dH}{dz} \right) + \rho c du + \left[\frac{\rho c^2 u}{u+c} - \frac{\mu H_{\theta}^2 (u-c)}{u+c} - \frac{\rho c v^2}{u+c} \right] \frac{dr}{r} = 0, \quad (10)$$

$$\text{where } C^2 = a^2 + b^2 = \frac{\tau p}{\rho} + \frac{\mu (H_{\theta}^2 + H_z^2)}{\rho},$$

$$\text{and } H^2 = H_{\theta}^2 + H_z^2.$$

WEAK SHOCK WITH WEAK MAGNETIC FIELD

Substituting shock condition (6) into (9) and neglecting the second and higher order term of ϵ , since $\epsilon \ll 1$ we get

$$\left(-\frac{\mu}{\tau P} (H_{\theta 0}^2 + H_{z 0}^2) \right) d\epsilon + \left(\frac{dP}{P} - \frac{da}{a} - \frac{dr}{r} + \frac{2\mu H_{\theta 0}^2}{\tau P} - \frac{2dP}{\tau P} \right) \epsilon = 0. \quad (11)$$

Now substituting $\frac{dP}{P}$, $\frac{da}{a}$, $\frac{\mu H_{\theta 0}^2}{\tau P}$ and $\frac{\mu H_{z 0}^2}{\tau P}$,

in equation (11) we get

$$\frac{d\epsilon}{\epsilon} = \left[\frac{[\tau(1-4\beta^2)-4]}{2\tau\beta} + \frac{1}{2\beta} \log \frac{A}{r} \right] \frac{dr}{r}, \quad (12)$$

where
$$\beta^2 = \frac{\mu(H_{\theta 0}^2 + H_{z 0}^2)}{\tau K_1},$$

$$\beta^2 = \frac{\mu H_{\theta 0}^2}{\tau K_1}.$$

Integration of equation (12) yields ,

$$\epsilon = \bar{K}_3 r^{\frac{[\tau(1-4\beta^2)-4]}{2\tau\beta} + \frac{1}{2\beta} \log \frac{A}{r}} \exp \left\{ -\frac{1}{2\beta^2} \left(\log \frac{A}{r} \right)^2 \right\}, \quad (13a)$$

where \bar{K}_3 is constant of integration .

In the case of diverging weak shock with weak magnetic field, we have the relation

$$E = K r^{-1/2} \left(\log \frac{A}{r} \right)^{-q} \exp \left\{ - \frac{3}{8} \beta \left(\log \frac{A}{r} \right)^2 \right\}, \quad (13b)$$

where K is constant of integration and

$$q = \left(\frac{3}{4} + \frac{\beta}{4} \right),$$

hence from equation (13a) and (13b) we have

$$\frac{u}{a} = 1 + \frac{\tau+1}{4} \frac{K}{3} r^{\frac{[\tau(1-4\beta)-4]/\tau\beta}{2}} \exp \left\{ - \frac{1}{2\beta} \left(\log \frac{A}{r} \right)^2 \right\}, \quad (14)$$

$$\frac{u}{a} = 1 + \frac{\tau+1}{4} K r^{-1/2} \left(\log \frac{A}{r} \right)^{-q} \exp \left\{ - \frac{3}{8} \beta \left(\log \frac{A}{r} \right)^2 \right\}, \quad (15)$$

for converging and diverging shock respectively

WEAK SHOCK WITH STRONG MAGNETIC FIELD

Substituting the shock conditions (7) in (9) we get

$$dE + \left\{ \frac{dP}{P} - \frac{\mu H^2}{\tau P} \left(\frac{dr}{r} + \frac{db}{b} \right) + \frac{2\mu H^2}{\theta_0 \tau P} \frac{dr}{r} - \frac{2dP}{\tau P} \right\} = 0, \quad (16)$$

substituting the respective quantities in equation (16)

we get

$$\frac{dE}{E} = \left[\frac{\tau(1+\beta+2\beta^2-2)}{1} \right] \left(\log \frac{A}{r} \right)^{-1} \frac{dr}{r}, \quad (17)$$

integrating equation (17), we get

$$E = \bar{K} \left(\log \frac{A}{r} \right)^{-\frac{q}{2}}, \quad (18a)$$

where \bar{K} is constant of integration and

$$q = \frac{\tau(1+\beta+2\beta^2-2)}{2\tau},$$

when we consider diverging shock with strong magnetic field we get,

$$E = \bar{K} \left(\log \frac{A}{r} \right)^{\frac{1}{2}(\beta-1)} \exp \left\{ -2\beta \frac{1}{1} \left(\log \frac{A}{r} \right)^{-1} \right\}, \quad (18b)$$

where K is constant of integration, equation (18a) and (18b)

disclose that

$$\frac{u}{b_0} = 1 + \frac{3}{4} K \left(\log \frac{A}{r} \right)^{-\frac{1}{2}} \quad (19)$$

$$\text{and} \quad \frac{u}{b_0} = 1 + \frac{3}{4} K \left(\log \frac{A}{r} \right)^{\frac{\beta-1}{2}} \exp \left\{ -2\beta \frac{1}{1} \left(\log \frac{A}{r} \right)^{-1} \right\} \quad (20)$$

for converging and diverging shocks respectively .

STRONG SHOCK

Substituting shock condition (8) into (9), we get

$$\begin{aligned} dU \left[\frac{2x}{Y} - \frac{N-1}{2} \left(\frac{x}{N} \right)^{\frac{1}{2}} \right] + U \left[-\frac{dp_0}{Y P_0} - \frac{2x}{Y} \frac{da_0}{a_0} + \frac{x(N-1)}{(N-1) - \sqrt{Nx}} \frac{dr}{r} \right] \\ + \left[L \frac{dp_0}{P_0} - \frac{\tau K N \beta}{P_0} \left\{ \frac{(N-1) + \sqrt{Nx}}{(N-1) - \sqrt{Nx}} \right\} \frac{dr}{r} + \frac{N \sqrt{Nx}}{[(N-1) - \sqrt{Nx}]} \right] = 0, \end{aligned} \quad (21)$$

Substituting the respective values , we get

$$\frac{dU}{dr} + \frac{B}{r} U - Cr^{-1} = 0,$$

where $B = \bar{B} / M$, $C = \bar{C} / M$

$$\bar{B} = \frac{x(N-1)}{(N-1) - \sqrt{Nx}}, \quad M = \frac{x}{Y} - \frac{(N-1)}{2} \left(\frac{x}{N} \right)^{\frac{1}{2}},$$

$$\text{and } \bar{C} = \frac{LK}{\rho} + \frac{\tau K N \beta}{\rho} \left\{ \frac{(N-1) + \sqrt{Nx}}{(N-1) - \sqrt{Nx}} \right\} - \frac{N \sqrt{Nx}}{(N-1) - \sqrt{Nx}}$$

integration of (22) yields,

$$U = K_5 \frac{2}{r} - \frac{B}{r} + \frac{C}{B}$$

where K_5 is constant of integration

In the case of diverging strong shock with strong magnetic field we have,

$$U = K_5 \frac{2}{r} - \frac{B}{r} + \frac{C}{B}, \quad (24)$$

where K_5 is constant of integration. Finally, for converging and

diverging shocks we have

$$\frac{U}{a_0} = \frac{1}{K \log \frac{A}{r}} \left(\frac{-B}{5} \frac{C}{B} \right), \quad (25)$$

$$\frac{U}{a_0} = \frac{1}{K \log \frac{A}{r}} \left(\frac{-B}{5} \frac{C}{B} \right), \quad (26)$$

respectively .

In the last, the expressions for the velocity, the density, and the pressure of the gas just behind the shock surface are.

(1) Weak shock with weak Magnetic Field .

$$u = k \frac{A}{r} \left(\log \frac{A}{r} \right)^{-\frac{1}{2}} \left[\tau(1-4\beta) - 4 \right] / \tau\beta \exp \left\{ - \frac{1}{2\beta} \left(\log \frac{A}{r} \right)^2 \right\}, \quad (27a)$$

$$u = k \frac{A}{r} \left(\log \frac{A}{r} \right)^{-\frac{1}{2}} \left[\tau(1-4\beta) - 4 \right] / \tau\beta \exp \left\{ - \frac{3}{8\beta} \left(\log \frac{A}{r} \right)^2 \right\}, \quad (27b)$$

$$\rho = \rho_0 \left[1 + k \frac{A}{r} \left(\log \frac{A}{r} \right)^{-\frac{1}{2}} \left[\tau(1-4\beta) - 4 \right] / \tau\beta \exp \left\{ - \frac{1}{2\beta} \left(\log \frac{A}{r} \right)^2 \right\} \right], \quad (28a)$$

$$\rho = \rho_0 \left[1 + k \frac{A}{r} \left(\log \frac{A}{r} \right)^{-\frac{1}{2}} \left[\tau(1-4\beta) - 4 \right] / \tau\beta \exp \left\{ - \frac{3}{8\beta} \left(\log \frac{A}{r} \right)^2 \right\} \right], \quad (28b)$$

$$P = K \left[\log \frac{A}{r} + \frac{\tau k}{3} \frac{[\tau(1-4\beta^2)-4]/\tau\beta^2}{1} \left(\log \frac{A}{r} \right) \exp \left\{ -\frac{1}{2} \frac{A}{r} \left(\log \frac{A}{r} \right)^2 \right\} \right] \quad (29a)$$

$$P = K \left[\log \frac{A}{r} + \frac{\tau k}{3} \frac{A}{r} \left(\log \frac{A}{r} \right)^{-1} \exp \left\{ -\frac{3}{8} \frac{A}{r} \left(\log \frac{A}{r} \right)^{-1} \right\} \right] \quad (29b)$$

(2) Weak Shock With Strong Magnetic Field

$$u = \beta K \bar{K} \left(\log \frac{A}{r} \right)^{-1} \quad (30a)$$

$$u = \beta K \bar{K} \left(\log \frac{A}{r} \right)^{-1} \exp \left\{ -2\beta \frac{A}{r} \left(\log \frac{A}{r} \right)^{-1} \right\} \quad (30b)$$

$$p = p \left[1 + \bar{K} \left(\log \frac{A}{r} \right)^{-1} \right] \quad (31a)$$

$$p = p \left[1 + \bar{K} \left(\log \frac{A}{r} \right)^{-1} \exp \left\{ -2\beta \frac{A}{r} \left(\log \frac{A}{r} \right)^{-1} \right\} \right] \quad (31b)$$

$$P = K \left[\log \frac{A}{r} + \frac{\tau K}{4} \left(\log \frac{A}{r} \right)^{-1} \right] \quad (32a)$$

$$P = K \left[\log \frac{A}{r} + \frac{\pi K}{4} \left(\log \frac{A}{r} \right)^2 \right] \exp \left\{ -2\theta \frac{A}{r} (1-\theta) \right\} \left(\log \frac{A}{r} \right)^{-1}, \quad (32b)$$

(3) Strong Shock With Strong Magnetic Field

$$u = \frac{(N-1)}{N} \left[\frac{K}{5} r^{-\frac{B}{5}} + \frac{C}{B} \right]^{\frac{1}{2}}, \quad (33a)$$

$$u = \frac{(N-1)}{N} \left[K r^{-\frac{B}{5}} + \frac{C}{B} \right]^{\frac{1}{2}}, \quad (33b)$$

$\rho = \rho_0 N$. For converging & diverging cases

$$P = K \log \frac{A}{r} \left[\frac{X \left(K r^{-\frac{B}{5}} + \frac{C}{B} \right)}{K \left(\log \frac{A}{r} \right)^{\frac{1}{2}}} + L \right], \quad (34a)$$

$$P = K \log \frac{A}{r} \left[\frac{X \left(K r^{-\frac{B}{5}} + \frac{C}{B} \right)}{K \left(\log \frac{A}{r} \right)^{\frac{1}{2}}} + L \right], \quad (34b)$$

where sections (a) and (b) denote the expression for converging and diverging shocks respectively.

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CHAPTER VIII

EFFECT OF ARTIFICIAL VISCOSITY ON THE EXPANSION OF
DISCONTINUITIES IN A ROTATING INTERPLANETARY MEDIUM

(1) INTRODUCTION

The propagation of strong shock waves in space, due to a surface explosion or impact has been treated in many levels of approximation. In one of these, an attempt is made to account for the material strength by including Newtonian viscosity term. S.W. Yuan [1,2,3] approximated the solutions of equations by seeking quasi-similar solution. In all of these solutions the viscosity coefficient is taken to be at most a function of time but independent of space coordinates. Pai [4,5] and Kumar [6] discussed the propagation of hydromagnetic cylindrical shock through a self-gravitating gas showing its velocity only for strong shocks. Recently Singh and Mishra [7] obtained analytical relations for shock velocity and shock strength and the expressions for the pressure, the density and the particle velocity immediately behind the shock assuming the fact that the initial density and azimuthal magnetic field distributions variables.

In the present chapter the characteristic method (Chester [8] Witham [9]) is applied to obtain expressions of the density, the pressure, the particle velocity just behind the shock propagating in a rotating atmosphere. The effect of Coriolis force is taken into account. Since the velocity effect has tendency to smoothen out such discontinuities, the artificial viscosity coefficient suggested by Richtmyer Von Neumann [10]

is introduced. The problem is discussed for two different cases
(i) for weak shocks and (ii) for strong shocks respectively.

(2) BASIC EQUATION BOUNDARY CONDITIONS AND ANALYTICAL EXPRESSION ----- FOR SHOCK VELOCITY -----

The equations governing the cylindrically- Symmetric flow of gas under the influence of its own coriolis forces in the presence of transverse magnetic field, Following Witham [7] are

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} + \frac{1}{\rho} \frac{\partial}{\partial r} (\rho + q) + \frac{H}{\rho} \frac{\partial H}{\partial r} + \frac{H^2}{\rho r} - \frac{v^2}{r} = 0 ,$$

$$\frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial r} + \rho \frac{\partial u}{\partial r} + \rho \frac{u}{r} = 0 ,$$

(2)

$$\frac{\partial p}{\partial t} + u \frac{\partial p}{\partial r} - \frac{[\tau p + (\tau-1) q]}{\rho} \left(\frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial r} \right) = 0 ,$$

$$\frac{\partial H}{\partial t} + u \frac{\partial H}{\partial r} + H \frac{\partial u}{\partial r} = 0 ,$$

$$\frac{\partial}{\partial t} (vr) + u \frac{\partial}{\partial r} (vr) = 0 ,$$

$$q = \frac{1}{2} \rho r^2 K \frac{\partial u}{\partial r} \left(\left[\frac{\partial u}{\partial r} \right] - \left(\frac{\partial u}{\partial r} \right) \right),$$

where $u(r,t)$, $p(r,t)$, $H(r,t)$, $v(r,t)$, and $\rho(r,t)$ respectively represent the velocity, pressure, magnetic field at distance (r) and time (t) and the density where $a^2 = \tau p / \rho$ and "q" is the artificial viscosity.

The magnetic hydrodynamic condition can be written in terms of a single parameter $N = \rho_1 / \rho_0$ as

$$\rho_1 = N \rho_0, \quad H_1 = N H_0, \quad u_1 = \left(1 - \frac{1}{N}\right) U,$$

$$U = \frac{2}{(\tau+1) - (\tau-1)} \left[a_0^2 + \frac{b_0^2}{2} (2 - \tau) N + \tau \right], \quad (2)$$

$$p_1 = p_0 + \frac{2 \rho_0 (N-1)}{(\tau+1) - (\tau-1)N} \left[a_0^2 + \frac{\tau-1}{4} b_0^2 (N-1) \right],$$

where 0 and 1 respectively stand for the states just ahead and just behind the shock front; U is the shock velocity, a_0 is the sound speed given by $(\tau p / \rho_0)^{1/2}$, and b_0 is the Alfvén speed

given by $\left(\frac{\mu H_0^2}{\rho_0} \right)^{1/2}$, where μ is magnetic permeability.

(2.1) WEAK SHOCK

For very weak shock we take the parameter as

$$\rho_1 / \rho_0 = 1 + \epsilon \quad (3)$$

Now consider the two cases of weak and strong magnetic field .

CASE I

For weak magnetic field $b_0^2 / a_0^2 \ll 1$. Under this condition the

boundary conditions (2) for very weak shock reduce to

$$\rho_1 = \rho_0 (1 + \epsilon), \quad H_1 = H_0 (1 + \epsilon), \quad u_1 = \epsilon a_0, \quad P_1 = P_0 (1 + \tau \epsilon), \quad (4)$$

$$U = \left(1 + \frac{\tau+1}{4}\right) a_0.$$

CASE II

For strong boundary magnetic field $b_0^2 / a_0^2 \gg 1$, using this condition and equation (3) the boundary conditions (2) reduce to

$$\rho_1 = \rho_0 (1 + \epsilon), \quad H_1 = (1 + \epsilon) H_0, \quad u_1 = \epsilon b_0,$$

$$P_1 = (1 + \tau E) P_0, \quad U = (1 + \frac{3}{4} E) b_0$$

(2.2) STRONG SHOCK

In the limiting case of a strong shock $\frac{P_1}{P_0}$ is large; and in the presence of the magnetic case this can be brought about in two ways.

CASE I

The purely nonmagnetic way when $N \rightarrow \frac{\tau+1}{\tau-1}$ is small.

When $b^2 \gg a^2$ or when $\mu H^2 \gg P$ that is when the ambient magnetic pressure is large compared with the ambient fluid pressure. In terms of N , the boundary conditions (2), now become

$$P_1 = N P_0, \quad H_1 = N H_0, \quad u = (1 - 1/N) U, \quad \frac{P_1}{P_0} = X(N) \frac{U^2}{a^2} + Y(N), \quad (6)$$

where

$$X(N) = \frac{(\tau-1)(N-1)^3}{2N[(2-\tau)N + \tau]} \quad \text{and} \quad Y(N) = \frac{N(\tau+1) - (\tau-1)}{(\tau+1) - (\tau-1)N}$$

For diverging shock the characteristic form of system of equation (1), that is the form in which equation contains derivatives only in (r, t) plane is

$$dP + \rho c du + H dH - H \frac{2(u-c)}{(u+c)} \frac{dr}{r} + \frac{\rho c^2 u}{(u+c)} \frac{dr}{r} - \frac{\rho c^2 v}{(u+c)} \frac{dr}{r} + \frac{cq}{r} \frac{dr}{(u+c)} + \frac{q(\tau-1)dr}{(u+c)} + \frac{q(\tau-1)u}{(u+c)} \frac{dr}{r} = 0, \quad (7)$$

$$\text{where } c^2 = a^2 + b^2 = \frac{\tau p}{\rho} + \frac{H^2}{\rho}, \quad \mu=1$$

Now we substitute the shock condition 4 or 5 or 6 into relation (7). A first order differential equation in (r) or u is obtained which gives the shock. For weak shock in the presence of weak transverse magnetic field, on substituting the shock condition (4) in (7), neglected the second and higher terms of E ($E \ll 1$), we obtain

$$\left[2 + \frac{H^2}{P} \right] dE + \left[\frac{dp}{P} + \frac{dH}{\tau P} + \frac{dr}{r} + \frac{da}{a} + \frac{q}{\tau P} \frac{dr}{r} + \frac{q(\tau-1)dr}{\tau P r} \right] E$$

$$= -\frac{2}{\rho_0} \left[-\frac{dP_0}{\rho_0} + \frac{1}{2} \frac{dH_0^2}{\rho_0} + \frac{H_0^2}{\rho_0} \frac{dr}{r} - v \frac{dr}{r} - \frac{q}{\rho_0} \frac{dr}{r} \right], \quad (8)$$

But by hydrostatic equilibrium prevalent in front of the shock

$$v \frac{dr}{r} = \frac{dP_0}{\rho_0} + \frac{1}{2} \frac{dH_0^2}{\rho_0} + \frac{H_0^2}{\rho_0} \frac{dr}{r} - \frac{q}{\rho_0} \frac{dr}{r}. \quad (9)$$

Hence equation (8) reduce to

$$\frac{d\epsilon}{\epsilon} = \frac{1}{2} \left(1 - \frac{H_0^2}{2\tau p_0} \right) \left(-\frac{dp_0}{p_0} + \frac{dH_0^2}{\tau p_0} + \frac{dr}{r} + \frac{da}{a} - \frac{q}{\tau p_0} \frac{dr}{r} + \frac{q(\tau-1)}{\tau p_0} \frac{dr}{r} \right) \quad (10)$$

Also we have

$$P_0 = - \left[\frac{-w}{w} \frac{p_0 v^2}{2} + \frac{(w-1)}{2w} \frac{H_0^2}{c} - \frac{-2w}{r} \right].$$

Inserting $\bar{w} = w/2$, we get

$$P_0 = \left[\frac{p_0 v^2}{w} - \frac{H_0^2}{2w} \right] r^{-w},$$

$$p_o = K_1 r^{-w} \quad (12)$$

$$p_o = p_c r^{-w} \quad (13)$$

$$a_o = K_2$$

$$\text{where } K_1 = \left[\frac{p_c^2}{w} - \frac{H_c^2}{2w} \right] ,$$

and

$$K_2 = \frac{\tau K_1}{p_c}$$

Positivity and finiteness of the equation pressure as defined by equation (12) requires that the constant (w) obey the inequality .

$$1 < w < 2 \quad (14)$$

Substituting dp_o / p_o and da_o / a_o in equation (10) we get

$$\frac{dE}{E} = \frac{1}{4} [2(w-1) + \beta(w+1)] \frac{dr}{r} + \frac{1}{4} (2-\beta) \frac{1}{\tau K_1} \frac{w}{[r dq - r^q (\tau-1) dr]} \quad (15)$$

Integrating the above equation we get, where for whole region

$$\int \partial q = 0,$$

$$E = r^{\frac{\tau+1}{2}} [2(w-1) + \beta^2 (w+1)] - \frac{1}{e} (2-\beta)^2 r^{\frac{\tau-1}{2}} q / \tau K_1^w, \quad (16)$$

Where $\beta = H_c / \tau K_1$ and K is constant of integration. With the aid of equation (4), we can write .

$$\frac{U}{K^2} = [1 + \frac{\tau+1}{4} Kr^{\frac{\tau+1}{2}}] - \frac{1}{e} (2-\beta)^2 (w+1) r^{\frac{\tau-1}{2}} q / \tau K_1^w, \quad (17)$$

$$\frac{U}{a_0} = [1 + \frac{\tau+1}{4} Kr^{\frac{\tau+1}{2}}] - \frac{1}{e} (2-\beta)^2 (w+1) r^{\frac{\tau-1}{2}} q / k w \tau_1, \quad (18)$$

Similarly for a strong magnetic field , by use of the shock condition (5) in (7) we get

$$\frac{dE}{E} = -\frac{1}{2} (1 - \frac{\gamma P}{2H}) \left[\frac{\tau}{2} \frac{dP}{H} + 2 \frac{dH}{H} + \frac{db}{b} + \frac{dr}{r} - \frac{q dr}{H^2} \right]$$

$$+ \frac{(\tau-1)}{2} \frac{dr}{r} \quad (19)$$

Substituting the value of $\frac{dP}{P}$, $\frac{dH}{H}$ and $\frac{db}{b}$ in the equation (19) and integrating we get

$$E = k r^{\frac{(3w-1)}{2}} \left[-\frac{1}{\beta^2} + 2(1-w) \right] e^{-\frac{1}{2}(1-\frac{w}{\beta}) q r^{\frac{w}{\beta}} (\tau-1)/w k \beta^{\frac{2}{\beta}}}, \quad (20)$$

where k is constant of integration. With the equation of (5) we write

$$\frac{U}{K^{\frac{1}{2}}} = \left[1 + \frac{3}{4} k r^{\frac{(3w-1)}{2}} \left(-\frac{1}{\beta^2} + 2(1-w) \right) e^{-\frac{1}{2}(1-\frac{w}{\beta}) q r^{\frac{w}{\beta}} (\tau-1)/w k \beta^{\frac{2}{\beta}}} \right]^{\frac{1}{2}} \quad (21)$$

$$\frac{U}{a^{\frac{1}{2}}} = \left[1 + \frac{3}{4} k r^{\frac{(3w-1)}{2}} + 2(1-w) \right] e^{-\frac{1}{2}(1-\frac{w}{\beta}) q r^{\frac{w}{\beta}} (\tau-1)/w k \beta^{\frac{2}{\beta}}} \quad (22)$$

For strong shock, if we substitute the shock condition (6) in (7) we get -

$$\left[\frac{x}{\tau} + \frac{1}{2}(N-1) \left(\frac{x}{N} \right)^2 \right] dU + \left[\frac{x}{\tau} \frac{dP}{P} - 2 \frac{x}{\tau} \frac{da}{a} + \frac{(N-1)}{(N-1)+(xN)} \frac{dr}{r} \right] U^2$$

$$+ EY \frac{dP}{p} + \frac{N H dH}{p} - \frac{H N [(N-1) - (XN)^{\frac{1}{2}}]}{p [(N-1) + (XN)^{\frac{1}{2}}]} - \frac{dr}{r} - \frac{N(NX)^{\frac{1}{2}} v}{[(N-1) + (XN)^{\frac{1}{2}}]} \frac{dr}{r}$$

$$+ \frac{(XN)^{\frac{1}{2}} q dr}{p [(N-1) + (XN)^{\frac{1}{2}}]} + \frac{q(\tau-1)(N-1)}{p [(N-1) + (XN)^{\frac{1}{2}}]} \frac{dr}{r} = 0, \quad (23)$$

substituting the values of $\frac{da}{a}$ and $\frac{dp}{p}$ we find that

$$\frac{dU}{dr} + B \frac{U}{r} + \frac{C}{r} + E r^w q + D r^{w-1} q = 0,$$

where $\bar{q} = q / r$,

and $\bar{B} = AB$, $\bar{C} = AC$, $\bar{D} = AD$, $\bar{E} = AE$,

$$\bar{B} = \left[\frac{(N-1)\tau}{(N-1) + (XN)^{\frac{1}{2}}} - w \right] \frac{x}{\tau}; \quad A = \frac{x}{\tau} + \frac{1}{2} \frac{(N-1)(\frac{x}{N})^{\frac{1}{2}}}{N},$$

$$\bar{C} = \left[\frac{-\tau K}{p_c} - \frac{N^2 H_c^2}{p_c} \frac{[(N-1) - (XN)]^{\frac{1}{2}}}{[(N-1) + (XN)]^{\frac{1}{2}}} - \frac{W}{2} \frac{N^2 H_c^2}{p_c} \right]$$

$$\frac{N(XN)^{\frac{1}{2}} - V}{[(N-1) + (XN)]^{\frac{1}{2}}}$$

$$\bar{D} = \frac{(\tau-1)(N-1)}{p_c [(N-1) + (XN)]^{\frac{1}{2}}}, \quad \bar{E} = \frac{(XN)^{\frac{1}{2}}}{p_c [(N-1) + (XN)]^{\frac{1}{2}}}$$

On integration, equation (24) gives

$$U = K r^{-B} - \left(\frac{C}{B} + \frac{r^W D q}{W + B} \right),$$

where K is constant of integration and we assumed that for

whole region

$$\int \frac{q}{r} dr = 0$$

(3) DISCUSSION

Finally the expression for the pressure and the particle velocity just behind the shock for above can be expressed as

$$P = K_1 r_1^{-w} + K_1 K_1 r_1^2 \frac{e^{[-2(w+1)+\beta(w+1)]} - \frac{1}{2}(2-\beta)^2 r_1^2 (\tau-1)^w q r_1^w}{e}$$

$$P = p_c r_c^{-w} + K p_c r_c^2 \frac{e^{[-2(w+1)+\beta(w+1)]} - \frac{1}{2}(2-\beta)^2 r_c^2 q(\tau-1)/\tau K_1^w}{e}$$

$$u = \epsilon a = K K_2 r_2^2 \frac{e^{[2(w-1)+\beta(w+1)]} - \frac{1}{2}(2-\beta)^2 r_2^2 q(\tau-1)/\tau K_1^w}{e}$$

(27)

$$P = K_1 r_1^{-w} + K K_1 r_1^2 \frac{e^{[(3w-1)/\beta + 2(1-3w)]} - \frac{1}{2}[1-\frac{1}{2}\beta]^2 q r_1^w (\tau-1)/\tau w K_1^\beta}{e}$$

$$p = p_c r_c^{-w} + p K r_c^2 \frac{e^{[(3w-1)/\beta + 2(1-3w)]} - \frac{1}{2}(1-(\frac{1}{2}\beta))^2 q r_c^w (\tau-1)/\tau w K_1^\beta}{e}$$

$$u = K K_2 r_2^2 \frac{e^{[2(w-1)+\beta(w+1)]} - \frac{1}{2}(1-(\frac{1}{2}\beta))^2 q r_2^w (\tau-1)/\tau w K_1^\beta}{e}$$

(28)

and for strong shock

$$P = \frac{K}{K_2} [x(N) K r_2^{-(w+B)} - (C/B) r_2^{-w} - \frac{dq}{B+w}] + K r_2^{-w} Y(N), \quad (29)$$

$$u = (1 - (1/N)) \left(K r - \frac{-B}{B} \frac{C}{B} - D \cdot q r \right)^{\frac{1}{2}} [w/(w+B)]$$

The expression (17) and (21) represent the propagation of weak diverging cylindrical shock wave through a rotating gas with effect of artificial viscosity in the presence of transverse weak and strong magnetic field respectively.

In relation (25) first term represents the solution obtained by the Witham, showing the effect of density distribution. The second term arises obviously on account of the coriolis force and the magnetic field. The velocity of magnetogasdynamic shock wave is determined by first term only when magnetic field is strong, for large values of r , the first term is very small in comparison to the second term.

As a consequence, the shock velocity attains a minimum value for a certain propagation distance beyond which the coriolis term stand dominating and shock propagation distance corresponding to the minimum value of the shock velocity may be obtained by equating

$$\frac{du}{dr} = 0$$

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